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Can microgrids make a major contribution to UK energy supply?

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Abstract

Almost all the electricity currently produced in the UK is generated as part of a centralised power system designed around large fossil fuel or nuclear power stations. This power system is robust and reliable but the efficiency of power generation is low, resulting in large quantities of waste heat. The principal aim of this paper is to investigate an alternative concept: the energy production by small scale generators in close proximity to the energy users, integrated into microgrids.

Microgrids—de-centralised electricity generation combined with on-site production of heat—bear the promise of substantial environmental benefits, brought about by a higher energy efficiency and by facilitating the integration of renewable sources such as photovoltaic arrays or wind turbines. By virtue of good match between generation and load, microgrids have a low impact on the electricity network, despite a potentially significant level of generation by intermittent energy sources. The paper discusses the technical and economic issues associated with this novel concept, giving an overview of the generator technologies, the current regulatory framework in the UK, and the barriers that have to be overcome if microgrids are to make a major contribution to the UK energy supply.

The focus of this study is a microgrid of domestic users powered by small Combined Heat and Power generators and photovoltaics. Focusing on the energy balance between the generation and load, it is found that the optimum combination of the generators in the microgrid- consisting of

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around 1.4 kWp PV array per household and 45% household ownership of micro-CHP generators-will maintain energy balance on a yearly basis if supplemented by energy storage of 2.7 kWh per household.

We find that there is no fundamental technological reason why microgrids cannot contribute an appreciable part of the UK energy demand. Indeed, an estimate of cost indicates that the microgrids considered in this study would supply electricity at a cost comparable with the present electricity supply if the current support mechanisms for photovoltaics were maintained.

Combining photovoltaics and micro-CHP and a small battery requirement gives a microgrid that is independent of the national electricity network. In the short term, this has particular benefits for remote communities but more wide-ranging possibilities open up in the medium to long term. Microgrids could meet the need to replace current generation nuclear and coal fired power stations, greatly reducing the demand on the transmission and distribution network.

Contents

1. Introduction and background

1.1. Some history

Public electricity supply in the UK began in 1881, but it was not until 1926 that the future direction of growth had been established. The generation and bulk transmission of electricity as well as its control were vested in one utility. This developed to take the form of large (up to 2000 MW) usually coal fired power stations feeding a high voltage (up to 400 kV) interconnected transmission network (the Grid). Twelve area-based utilities bought the electricity in bulk, distributed it via lower voltage feeders and sold it to

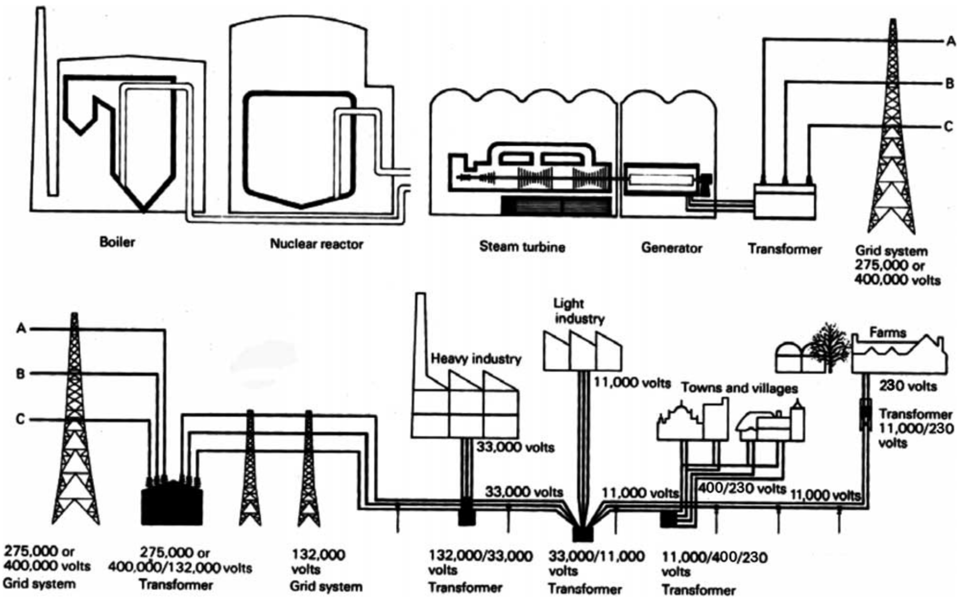

Fig. 1. A typical electricity transmission and distributions system, illustrated on the example of the UK public electricity supply. Most generators considered in this paper would be connected at 415/230 V voltage (adapted from R. Cochrane, Power to the People, CEGB/Newness Books, 1985).

consumers at various voltages, from 33 kV to 240 V Fig. 1. This situation prevailed in several forms until 1989, the most prominent feature being the control of generation, bulk transmission planning and the bulk supply tariff being under the control of one utility.

The Electricity Act of 1989 both split the industry into many separate parts and privatised it. Also introduced was an Office of Electricity Regulation (OFFER) with a primary responsibility for promoting competition and protect the consumer. The generating stations were privatised and sold their electricity on the open market. The market was facilitated by a transmission network (privately owned and managed) and a number of Distribution Network Operators (DNOs). None of these 'network owning' companies bought or sold electricity—their revenue came from the transmission or distribution of electricity.

Electricity Suppliers bought from the generators and resold to customers, the price being controlled by the market place. This situation existed, again in several forms, until today, when the New Electricity Trading Act (NETA) has altered pricing and charging methods.

1.2. Distributed generation

The use of renewable energy sources for the generation of electricity is seen as one of the important ways of reducing carbon dioxide emissions. Whilst some of these sources can produce large power outputs in single power stations (hydropower or geothermal power, for example) the majority are relatively small in size. This means such generators

are more conveniently (and cheaply) connected at lower voltages within the distribution system. It was never envisaged that this system would be required to support the connection of generation.

A similar situation exists with combined heat and power (CHP) units which produce both electricity and heat. In the UK, almost 50% of the primary energy consumption is used to provide heating and hot water in buildings [1] and the aim of CHP is to supply this low-grade heat alongside electricity generation. The advantages of a high overall efficiency of energy production which are thus attained must be offset against the necessity to operate smaller units close to the consumer, and usually need to operate a district heating system to distribute the heat. The term ‘distributed generation’ is used to describe these generators (typically small renewables and CHP, but also other on-site electricity generators) connected to the distribution system. A synonymous term also used is ‘embedded generation’, describing generators embedded within the distribution system. Connection of generation in this way poses many technical, commercial and safety issues; all of which must be tackled in order to allow a wide penetration of renewable generation.

In addition to the problems posed by distributed generation, the use of renewable sources and CHP usually adds more specific issues related to the actual method of generation used. An example that can be used to illustrate this point is photovoltaic (PV) generation. There is no generation at night, which is of course predictable but in addition, the sun can be obscured by cloud cover on a random basis. A similar situation exists with CHP which is normally controlled to supply heat, with electricity production as a by-product. These phenomena change in all time scales leading to a constantly changing electrical output. As a source of electrical energy this has some disadvantages which, in the present format, have to be addressed by the operators of the public electricity supply.

Consumers have become used to electrical power available on demand. They do not need to structure their load pattern, the entire responsibility for matching power and demand is placed upon the utilities, which must have enough generation available at all times. With more creative thinking about the way energy is supplied, used and controlled it may be possible to satisfy the demand for energy, but accommodate the fluctuating resources which are a feature particularly of renewable energy sources. This may be possible by ensuring a satisfactory mixture of sources and loads to enable the demand and supply to match.

1.3. Why microgrids?

A microgrid is a small-scale power supply network that is designed to provide power for a small community. The definition of the ‘small community’ will be discussed in more detail in Section 2, but may range from a typical housing estate, isolated rural communities, to mixed suburban environments, academic or public communities such as universities or schools, to commercial areas, industrial sites and trading estates, or municipal regions. The key concept that differentiates this approach from a conventional power utility is that the power generators are small (often referred to as micro-generators, of a similar size as the loads within the microgrid), they are distributed and located in close

proximity to the energy users. The generators, and possibly also loads, are controlled to achieve a local energy and power balance.

In the commercial world, these developments in distributed generation have been compared with the changes currently taking place in the telephone industry [2] and it has been estimated that, within a decade, the market for such equipment will exceed $60 billion a year. The US Electric Power Research Institute [3] and ABB even see the emergence of ‘virtual utilities’ which, by analogy with the Internet, will allow intelligent metering and switching and result in reduced environmental impact, greater system reliability and lower operating cost. The motivation behind this study lies in the potential of the microgrid concept to deliver a significant reduction of CO_2 emissions, for the following reasons:

- The use of both electricity and heat permitted by the close proximity of the generator to the user, thereby increasing the overall energy efficiency.
- Significant environmental benefits made possible by the use of low or zero emission generators including PV arrays and fuel cells.
- Low impact on the electricity network, by virtue of good match between generation and load, despite a potentially significant level of generation by intermittent energy sources.

1.4. Issues to consider

Although examples of networks similar to microgrids exist, there are technical and regulatory issues that need to be considered before this concept can be applied on a wider scale. The principal issue to consider is how closely the energy supply (both electricity and heat) within the microgrid can satisfy the local loads. The answer to this question will help decide how the microgrid interacts with the main utility, and the nature of the connection to be determined. Indeed, it may even be desirable in some circumstances for the microgrid to be disconnected from the utility, and operate as ‘stand-alone’. The issues that must be resolved to permit this type of operation include:

(i) *Precise energy and power balance within the microgrid*, on a time scale ranging from milliseconds to years. Over the short time scale, the power balance is linked to the question of control; over longer time scales, one needs to consider the relationship between energy supply, demand and storage. Similar arguments are used to design stand-alone power supplies, for example, photovoltaic or hybrid systems which power remote equipment or serve isolated rural communities across the world.

(ii) *The nature of connection with the main utility (the ‘grid connection’).* An arrangement which would permit the microgrid operator the choice to operate in the ‘grid connected’ or ‘stand alone’ mode is an uncharted territory for conventional power utility engineers, and issues remain both at the technical and regulatory level.

(iii) *Energy storage*. The conventional utility supply operates on the principle that power is generated when it is required. Energy storage introduces a novel component in

a utility supply and broadens the design criteria. On a quantitative level, the size of the energy store is intimately linked to the energy balance and to the required security of supply provided by the microgrid.

(iv) *Demand management*. The temporal mismatch between generation and load can be alleviated by managing the demand. The shifting of load facilitates achieving the energy balance and helps reduce the size of energy storage. Whilst experience exists of demand-side management at industrial level and lessons can be learned from concepts such as storage heating, demand management at the domestic level is attracting much interest in the research community [4] but further experience is needed before routine applications become commonplace.

(v) *Seasonal match between generation and load*. Energy storage and demand management can be effective to achieve energy balance at the diurnal time scale. A sufficient energy must be available from the generators to ensure energy balance over longer time scales if a microgrid powered by renewable or other intermittent energy sources such as micro-CHP is to be capable of stand-alone operation. This can usually be achieved only by a diversity of generation methods appropriate to the load.

1.5. Structure of the paper

This paper addresses the technical and economic issues associated with the integration of small generators into microgrids, serving to depict the essential features of de-centralised electricity generation combined with on-site production of heat. An overview of the field is given, including the technology and the economic and regulatory framework. The technical aspects are discussed with focus on the generators and load profiles, the utility connection and the control of the microgrid. The regulatory framework is reviewed based on the current position of the UK Government and views of the industry.

A principal novel contribution of the project is a model which allows a detailed analysis of the microgrid in terms of the relationship between the energy supply, demand and storage. It is shown by using the example of a microgrid consisting of domestic dwellings in the UK powered by domestic micro-CHP generators and PV arrays how an optimum mix between these generators can achieve a good seasonal balance between energy production and demand, both for electricity and heat. Energy storage provides a bridge between the daily generation and usage profiles. Although electricity storage in rechargeable batteries is the most immediate option, more innovative solutions may be developed in the future to make use of the effective thermal storage (hot water in the hot water tank, heat retained in the fabric of the building). The management of demand (for example, washing machines, tumble driers and dish washers) can be used to reduce this storage significantly.

Economics of the microgrids is then considered in the light of the technology analysis developed in the project. Several scenarios are identified for possible future developments. The paper also raises some economic and institutional questions that will need to be overcome if microgrids are to be deployed on a large scale in the UK.

2. Microgrids

2.1. The microgrid concept

The microgrid is a concept based around the assumption of a cluster of electrical and thermal loads together with small scale sources of electrical power and heat [5]. The power sources will generally be mixed, including renewable sources such as photovoltaic or wind generators together with fossil fuelled generators meeting local heating requirements and generating electricity (cogeneration). The connection between this network and the wider electrical power network will be through a well defined and controlled interface. The microgrid is responsible for servicing the needs of its consumers, ensuring a quality of supply and possibly controlling some of the non-critical loads. The interface with the local electricity utility will be one of exchanging power so that the microgrid will look like a well behaved load or generator.

A potential advantage of this approach is that it should facilitate more imaginative schemes for meeting the local requirements in a flexible manner with the small scale generators and consumers closely integrated. For example, at the electrical utility scale, load control to help match short term supply and demand has proved very hard to implement. Although, the ownership and operation issues for the microgrid concept have yet to be addressed, one possible way forward might be for a microgrid as intrinsically a local ‘co-operative’ venture. In such systems, the consumers may also be the suppliers and so a more imaginative approach to load control may be possible in the joint interests of cost and efficiency. In particular, the microgrid will need to encourage consumers to participate in small scale cogeneration, photovoltaics, and other renewable energy schemes. Metering and charging arrangements within the microgrid would be agreed locally and would have to reflect the market for power within the microgrid. The microgrid concept is made possible by the recent advances in small scale, reliable generators, power electronics and digital controllers that make it possible to reverse the trend to large scale generation and bulk supply.

The key feature of the microgrid is that there should be local electricity generation that matches the power requirements in the microgrid. There are various types of generator that may be considered. Photovoltaic generators are attractive if the environment is primarily residential since they may be incorporated into buildings in an unobtrusive manner. Very small scale cogeneration schemes can be based on gas boilers for central heating and domestic hot water. Possible technologies for this are fuel cells or Stirling Engine powered generators. For a microgrid including commercial or light industrial premises than larger cogeneration schemes based on gas turbines or other prime movers may become appropriate.

Energy storage will probably be required to accommodate the variations of available generation and power demand. Short term storage of electrical power will be necessary to help accommodate the rapid fluctuations of load or generation that may be anticipated on a relatively small network. Over longer time scales, energy management made possible by storage can be used to make the most efficient use of photovoltaic generation or the electricity produced by micro-CHP. Some energy storage may be possible in the form of domestic hot water or as part of space heating.

The microgrid may exist as a remote power system in regions where utility supply is not available. It may, on the other hand, be embedded in a larger electrical utility—this would be the typical situation, for example, in the UK with a mature utility power system. In this instance, two control issues need to be addressed: the relationship between the microgrid and the local utility, and the question of internal control. These topics are the subject of Sections 2.2 and 2.3.

2.2. The relationship between the microgrid and a local electricity utility

The intention is that the microgrid be self-sufficient, but for security of supply and flexibility it would almost certainly be connected to the local electrical utility network, or even to adjacent microgrids. These links may be bi-directional enabling the import or export of electricity, or, depending on commercial considerations, it might just be a unidirectional flow of power. From the point of view of the microgrid, the utility connection might be viewed just as another generator or load.

This raises the question as to whether or not the microgrid should be linked to other networks over a synchronous alternating current (AC) connection. The advantage of a synchronous link would be its simplicity, requiring only an electrical interconnection, circuit breakers and probably a transformer. Lasseter [5] has considered this possibility and shown that in principle it should be possible to run a microgrid with minimal central control of local generation which is able to operate connected to the utility, or, in the event of loss of the connection, move smoothly into stand-alone or island operation with no loss of power to the microgrid. What is perhaps less clear is how the synchronous connection would be re-synchronised once the utility was ready to re-establish the connection.

The alternative approach would be an asynchronous connection using a direct current (DC) coupled electronic power converter. This might be bi-directional, enabling import and export of power or simply a device to import power when local resources were inadequate. An advantage of this approach is that it isolates the microgrid from the utility as regards reactive power, load balance, etc. Only power is exchanged with the utility, the microgrid is entirely responsible for maintaining the power quality (frequency, voltage and supplying reactive power and harmonics) within its area.

With an asynchronous link the microgrid might be unusual that all its power will be supplied through electronic inverters. Some generators, such as photovoltaic cells are intrinsically sources of DC and hence need inversion to connect them to an AC network. Others, for example, microturbines or Stirling engines may generate AC but are not well suited to operate a synchronous generator because the frequency is unsuitable or variable. Voltage source inverters with suitable control schemes will be required to permit stable operation of the network with many small generators attached. Fortunately, advances in power electronics and digital controllers mean that sophisticated control strategies are possible and the cost need not be excessive. Which of these approaches is more appropriate may well depend on the size of the microgrid. It may also depend on the regulatory environment governing the interchange of power between the microgrid and the utility.

2.3. Internal control of a microgrid

There are many commercial and political issues concerned with control; however, the technical problems of a microgrid must be managed, for the concept to become a reality. The control of a microgrid is intimately tied with the energy and power balance in the microgrid, and the question of energy storage. There are three main parameters—frequency, voltage and power quality—that must be considered and controlled to acceptable standards whilst the power and energy balance is maintained.

2.3.1. Power balance

A power system usually contains no significant energy storage; the generated and dissipated power must, therefore, be constantly kept in balance. There are specific circumstances in which energy storage is significant, and these are discussed in Section 2.5. This power balance must be maintained on a cycle-by-cycle basis if the system is to maintain its frequency. Too much generation and the system accelerates, to little and it slows; neither situation is acceptable. The permissible frequency deviation is defined by Statute, and in the UK it is the responsibility for the NGC to ensure that this deviation is not exceeded. Since the whole of the UK is run as one synchronous system, any new generator means the disconnection of another or a rise in load, if the system frequency is to remain constant. Power balance in a microgrid is, therefore, essential for frequency control.

In a microgrid, frequency stability becomes critical; therefore, control is a major concern. There are a number of techniques used to restore the power balance and hence correct the frequency: the use of load shedding, increase in primary generation and recovery of stored energy. All of these are available within a microgrid, but because the system is small the problem is much more difficult to manage to the same standard as is normal in a utility system.

Short-term storage of energy is needed to cope with the fluctuations in power demand or accommodate the sudden loss of some generation. A microgrid with many small generators will not be an intrinsically stiff system, unlike a national interconnected utility. The small generators will neither store significant energy in their mechanical inertia, nor will they necessarily respond quickly to sudden changes of load. Short term storage, probably distributed with the generators, will permit the inverters to follow the rapidly changing demand while giving time for the generators to respond, or extra generation to be brought on line or for generators to be closed down. This same storage could be used to help accommodate the diurnal variation of demand.

There are two related issues, firstly quite small power imbalances will produce large frequency excursions and secondly they will happen much more quickly. The first issue may also be an advantage for a microgrid since small energy stores will have significant effects. The second issue means that stored energy recovery must be fast and precise. Since the most probable store, in the near future is likely to be a battery with an inverter, this does not pose an insurmountable problem; such a system is quite fast enough to ensure adequate frequency control.

2.3.2. Frequency

The UK power system operates at 50 Hz and there are obvious advantages in adopting this frequency, whether there is to be a synchronous connection or not. The frequency limits are laid down by law and are relatively tight though not to the same standards as some other power systems. There is, however, no reason to adopt these standards and some relaxation could be possible (in a non-synchronous system) if it were advantageous. It is doubtful, however, that limits larger than ± 0.5 Hz could be acceptable. Frequency therefore must be controlled to within these limits.

The 'normal' method of frequency control in the UK power system is by control of the rotational speed of the synchronous machines supplying the power. Within a large interconnected system, with many synchronous generators, no single machine can control the frequency, there being a flow of 'synchronising power' into any machine that is slowed in order to keep it in synchronism. There needs to be a large power imbalance to alter the speed and hence frequency of the system, of the order of 5000 MW per Hz for the UK.

The fewer the number of machines, the less stiff the system and frequency control becomes a technical issue. Machines in such a system must be able to respond quickly to load variations in order to preserve the power balance at all times. This means rapid detection of frequency change and fast, accurate control of load generation, or both.

Not all renewable generators are synchronous machines: wind turbines are often induction generators and photovoltaic arrays connect to the system through inverters. These two require very different frequency and load control in order to satisfactorily operate in a system. Inverters can be used to control frequency since the inverter frequency can be controlled independently of load. However, inverters do not behave as rotational synchronous generators and require different philosophies.

2.3.3. Voltage

The system voltage within a large multi generator system is controlled by initially the voltage of the machines but also by the reactive flow. In general, the reactive balance becomes more critical in a smaller system. For example, all reactive demand must be supplied from one generator in a single machine system. This is not strictly true, but adds significantly to cost and control problems if reactive demand has to be compensated by extra static plant.

A conventional distribution system is usually a feeder network, and there is little interconnection. Voltage drop along feeders becomes an issue, as it will vary with load and distance along the feeder. This dictates that any simple microgrid will have to be either small to be satisfactory or be specially designed as an interconnected network.

The voltage and its limits at consumer's terminals are specified by law, but they are reasonably wide. With proper design, production of the correct voltage should not be an insurmountable problem.

2.3.4. Power quality

Control of power quality will be the biggest issue for a microgrid. Voltage dips, flickers, interruptions, harmonics, dc levels, etc. will all be more critical in a small system with few generators. There will need to be a critical appraisal of both the effects and consequences of relaxing and/or enforcing standards in this area.

As has been discussed by Venkataramanan and Illindala, the distributed generation within the microgrid could enable better control of power quality [6]. With electrical storage together with the distributed generation power quality could be maintained in much the same way as is achieved by Uninterruptible Power Supply (UPS) systems. The electronic inverters can not only supply power at the fundamental frequency, but also generate reactive power to supply the needs of reactive loads, cope with unbalanced loads and generate the harmonic currents needed to supply non-linear loads.

2.4. Energy balance

Little significance is usually attached to the concept of energy balance in a conventional system: the solution is just to add more fuel over time. A microgrid which contains a high proportion of intermittent energy sources—be it renewables such as PV or wind, or energy sources controlled for other purposes such as micro-CHP—is not able to do this. The energy available to the system is finite and depends on matters that cannot usually be controlled or even predicted with any certainty.

If such a source is to be used and achieve levels of reliability similar to those of conventional plant, energy storage is essential. It is also clear that, as the diversity of the generation methods in any system is reduced, the role of energy storage becomes more dominant. It, therefore, appears desirable that any microgrid should employ more than one method of generation as well as some form of energy store.

The diversity of generation methods is particularly important if the microgrid is to operate stand-alone. The microgrid must then contain sufficient generation capacity and type that can supply adequate amounts of energy with sufficient reliability. Photovoltaic arrays, for example, are a reliable power source during the summer months. They combine well with generators such as micro-CHP which generate most power in winter to provide heat for domestic dwellings. This point will be taken up further in Section 5 which examines the sizing of generators and storage.

2.5. Energy storage

There is no economic general purpose method for the storage of electricity *per se* in the quantities required for public utility use. There are of course methods involving capacitors and super conducting magnets; both of which are technically complex and with present knowledge, rather expensive, but nevertheless used in specific situations. Because the direct storage of electricity is not very practical, the storage of energy by other methods, for later use in electricity generation is employed. These are many and varied, depending upon the situation and the purpose for which the electricity is to be used.

It is likely that a microgrid will rely on chemical energy storage in the form of electric batteries. In the simplest of systems this will mean lead acid cells, which are well developed, available, predictable and robust. For more sophisticated applications, redox batteries are becoming available, and development will continue. In critical situations, where cost is not an issue, the application of super conducting energy storage has been used. Again, continued development is expected to both reduce costs and to increase reliability. Over shorter periods of time, the use flywheels may be appropriate (Table 1).

Table 1
Possible energy storage technologies for a microgrid (adapted from www.energystorage.com)

Device	Discharge time	Power	Comments
Batteries (lead acid, NaS, Li-ion, NiCd)	Hours	Up to tens of MW	Technologies range from highly developed to research stage. A wide range of uses, lifetimes and costs
Regenerative fuel cells (flow batteries)	Hours	Hundreds of kW to about 10 MW	Some flow batteries used commercially; others still in demonstration stage
Flywheels	Seconds to minutes	Ten to hundreds of kW	Little maintenance, long life (10 s of thousands of cycles) and environmentally inert material. Can bridge the gap between short and long term storage
Supercapacitors	Seconds	100 kW–1 MW	Lower energy density than lead acid batteries but long life (10 s of thousands cycles); fast charge and discharge capability
SMES	Seconds to minutes	10–100 MW	Storage of electrical energy-no conversion required; virtually no losses. Cryogenic hardware required. Low volume production at present
Hydrogen	A wide range of options, as part of the hydrogen economy. See, for example, Tyndall project IT1.26 at www.tyndall.ac.uk for more detail.		

The more common forms of large-scale utility storage (hydropower or even compressed air) are probably too large and too site specific to be appropriate for most microgrid applications.

The calculation of battery size (energy), and inverter rating (power), will depend on the size of the loads and generators within the microgrid, as well as its topography. As an alternative to storing energy, the shedding of load is more likely to be used in a microgrid, rather than a large scale public utility, because it is easier to identify those loads which are least critical. Where cogeneration is used, some of this energy storage may well be in the form of heat. This storage could be in the form of domestic hot water or stored for use in space heating. Innovative control strategies can be developed to make use of this storage and, if necessary, the plant may be run to meet the electrical load when there is no demand for thermal energy.

3. Generators and loads

3.1. Introduction

The wide range of potential generators within the microgrid share one common feature: they are small, and comparable in size to the loads within the microgrid. It is also likely that several different types of generators will be present, adding a diversity of generation to the diversity of loads. This issue is particularly important when considering the seasonal aspects of the energy balance in the microgrid (discussed in Section 5).

The focus of this study is microgrids comprising of domestic CHP units and photovoltaic array. A broad overview of these generators is given in this section, as appropriate to the energy balance purposes of this work. Also included is a brief overview

of a typical domestic load, and the effective averaging that occurs when the load of several households is combined. The connection of small generators within the microgrid will be an important integration issue, and the related utility connection aspects (recently aired internationally with focus on small photovoltaic generators) are reviewed in Section 3.5.

3.2. Photovoltaic arrays

The photovoltaic array consists of one or several modules mounted on support structures and electrically connected to form a DC power producing unit. The modules are most commonly based on crystalline silicon solar cells although thin film modules using amorphous silicon, cadmium telluride or copper indium diselenide (CIS) have also recently become available. The array is connected to the utility distribution network through an inverter. A comprehensive overview of photovoltaic power generation technologies, including the system aspects, is available from two recent Handbooks on this subject [7,8].

To maintain an optimum point on the power characteristic of the array, the DC interface of the inverter incorporates a maximum power point tracker. The output from the PV array is then closely related to its rated power P_o and to the solar irradiance. The expected daily energy produced by a PV array can be estimated from the expression

$$E_d = P_o(\mathrm{PSH}) \tag{1}$$

where PSH—Peak Solar Hours—is equal to the mean daily solar radiation in kWh/m^2 at the site of the installation. Table 2 shows the typical values of mean daily solar radiation for several cites with different climates. A more accurate estimate can be obtained by correcting (1) for the inclination of the panels and reflection from the ground. The reduction in cell efficiency on account elevated operating temperatures of the solar cells and system losses should also be allowed for (see, for example, Chapter IIIa in Ref. [7]).

Photovoltaic arrays integrated in the roofs and facades of buildings are becoming an increasingly common method of power generation within the urban environment. Large-scale government support programs in Japan and Germany are driving the industrial production but many other countries (including UK) provide subsidies for

Table 2
Examples of the mean daily solar radiation (in kWh/m^2, equal to the Peak Solar Hours) for various locations in the world (see Part1 in Ref. 27)

	Mean daily radiation (kWh/m^2)
Stockholm 59.35 N	2.52
London 51.52 N	2.55
Freiburg 48.00 N	3.04
Geneva 46.25 N	3.31
Nice 43.65 N	4.03
Oviedo 43.35 N	3.18
Porto 41.13 N	4.26
Heraklion 35.33 N	4.44
Sde Boker 30.90 N	5.70
Ilorin 8.58 N	4.19

the installation of photovoltaic generation. The perception of solar cells as a building component has an impact on non-technical aspects of photovoltaics, for example, on the required pay-back times for photovoltaic generators. This issue will be taken up again in Section 6.

3.3. Fossil fuel power generators

3.3.1. Combined heat and power generators

Within the context of a microgrid all fuel powered generators of electricity may be assumed to be included within a combined heat and power (CHP), or cogeneration, scheme to ensure maximum energy efficiency. When connected to a power utility it is usually assumed that in order to gain the maximum benefit these generators will run primarily to match the thermal load with electricity as a by-product. In the context of a microgrid this will not necessarily be the case since the generation may be required to meet the electrical load. This raises two issues: does the ratio of electrical to thermal load match the generator and is thermal storage possible, perhaps as domestic hot water. There may also be a requirement that some generators are equipped with alternative cooling arrangements so that the microgrid is able to meet the electrical demand using fossil fuelled generators even if the thermal load is not required.

Reciprocating gas or oil fuelled engines are probably the best established prime movers for small to medium scale CHP systems although micro-turbines or Stirling cycle external combustion engines are alternatives that are being developed and trailed. An alternative approach is to replace the heat engine prime mover with a fuel cell which is able to convert the energy from the fuel directly to electricity while also providing a significant thermal output (see Table 3).

3.3.2. Reciprocating internal combustion engines

These engines can broadly be split into two groups, compression ignition (diesel) engines and spark ignition engines. Compression ignition engines run from diesel fuel or heavy oil. They are well developed having been widely for many years for small scale electricity generation, standby generators, etc. The principal concerns with engines of this type is that they need heavy oil as a fuel and generate significant pollution from oxides of nitrogen and particulates. Spark ignition engines may run from a variety of fuels, but for domestic generation natural gas is likely to be most attractive where it is available. Low frequency acoustic noise is also an issue for internal combustion engines that are to be used in a domestic environment. Combined heat and power systems based on these technologies and suitable for the domestic scale are available from a range of suppliers [9].

An attractive feature of these power sources is that they can start-up quickly and respond rapidly to changes in load.

3.3.3. Micro-turbines

Small scale gas turbines are being developed for small scale generation, although much of the effort has been aimed at generators in the region of 30–100 kW (electric), significantly larger than the size envisaged in this study. Smaller generators of order

Table 3
Fossil fuel power sources for a microgrid

Prime mover	Fuel	Ratio of thermal to electrical power	Advantages	Disadvantages	Commercial status
Internal combustion engine	Diesel, heavy oil, natural gas	2–3	Well established technology, good load following, rapid start-up, maintenance skills readily available	Noise, emission of NO_X and particulates esp. from compression ignition engines	Available now
Micro-turbine	Natural gas	~2	Lower noise than internal combustion engine, efficient combustion with low emissions of NO_X, fast start and good load following	High speed and temperature requires sophisticated materials, may be difficult to achieve efficiency in small sizes	Developmental in small sizes, larger ratings available
Sterling engine	Natural gas, other fuels possible	3–6	Low noise, efficient combustion and low emissions, robust, low maintenance	Load following less good than for internal combustion engine	Prototype systems being subjected to large scale tests
Fuel cell	Natural gas, hydrogen	1.5–2	Only moving parts for auxiliary systems (pumps/fans), have the potential for high electrical efficiency	Relatively complex because of need to reform fuel if natural gas is used, slow start-up especially for high temperature cells	Developmental

2–5 kW have been demonstrated [10], but there are significant challenges in producing a system which is economically viable. The main attractions of the gas turbine approach are efficient combustion, flexibility of fuel and potentially low noise and vibration. There are, however, significant engineering challenges from the high temperature and high speed required for the turbine.

There is also significant activity related to larger microturbines with power ratings between 25 and 250 kW, in which a permanent magnet generator is directly coupled to a small gas turbine. A recuperator is normally used to recover some of the exhaust heat and boost efficiency to around 30–35%.

Leading companies in the area include Bowman Power Systems Ltd (35–60 kW), Capstone (28–60 kW), and Turbogenset (60 kW?), Elliots (80 kW) and Pratt and Whitney (80 kW). A good overview of the state of the art is presented in books written by Hamilton [11] and Moore [12] and a paper by Nicholas [13]. Davis [14,15] makes the case for using the technology in a Microgrid system.

Tests on actual systems produced by Bowman and Capstone [16,17] revealed that these systems are still not very reliable. In general, the technology is viewed as promising, but it is still in its infancy with many teething problems.

3.3.4. Stirling engines

The Stirling Engine has recently attracted attention as a power source for small generators. The attraction of this prime mover is that as an external combustion engine almost any heat source may be used (e.g. solar power has received considerable attention with possible applications in space). The external source of heat means that for conventional fuels the burner may be optimised to achieve efficient combustion and low pollution.

The Stirling Engine has a thermodynamic cycle that requires a relatively complex mechanical system usually involving two pistons, or a piston and a displacer. Two types of engine are recognised: the kinematic engine which uses a conventional crank mechanism for the pistons and produces a rotary motion and the free piston engine in which the piston and displacer oscillate linearly on springs. To produce electricity the kinematic engine will drive a conventional rotary generator. The free piston engine generally requires a linear generator. Both types of Stirling engine are being developed for domestic scale CHP systems [9].

Stirling engines have the advantages of potentially high thermodynamic efficiency (the Stirling cycle is reversible), continuous external combustion and low noise. However, the complexity of the motion, the need for a thermal store (regenerator) and difficulties with lubricating the piston and displacer are challenges to the engineer. As an external combustion engine the thermal capacity of the system will limit the speed at which it can start-up and the speed with which it can follow variations in load.

3.3.5. Fuel cells

Fuel cells generate electricity directly from the reaction between fuel and oxidant without the need for a heat engine and a mechanical system. A number of fuel cell types have been developed, some require high temperatures to operate, e.g. the solid oxide fuel cell (SOFC) requires a temperature of 800 °C, others require lower temperatures, e.g. the proton exchange membrane (PEM) cell requires a temperature of up to 90 °C. Operation is complicated by the need to convert hydrocarbon fuels into hydrogen in a reformer before the fuel can react in the cell.

A domestic scale CHP system based on a PEM fuel cell has been demonstrated [18]. This system operated at a power level of 4 kW electrical power and 6.8 kW thermal. This paper highlights some of the problems associated with current fuel cell technology, particularly the complexity and inefficiency associated with the fuel processor required to generate hydrogen from natural gas. The fuel cell also had a poor load following capability and was reinforced with battery storage to allow the system to follow the load and accommodate short duration peak loads.

3.4. Electrical power generation

Internal combustion (IC) engines and kinematic Sterling engines may use conventional rotary generators. With available micro-CHP systems based on IC engines, induction generators seem a popular choice [9]. While these are attractive on grounds of simplicity, cost, low maintenance and ease of starting up they are more appropriate for use connected

to a stiff utility network rather than a microgrid. Synchronous generators may be more appropriate in this case.

All the other sources will need electronic conversion to achieve a conventional 50/60 Hz supply. Micro-turbines operate at high rotational speed giving a high frequency from the generator which must be rectified and converted electronically to AC. Free piston Sterling engines most simply use a linear generator. The frequency of generation depends on the resonant frequency of the piston and displacer systems in the engine. Hence, this type of generator is unlikely to be suitable for synchronous generation. Fuel cells are intrinsically generators of DC and so will require a power inverter.

It is clear that power electronics will play a key role in a microgrid to provide efficient conversion from the generator to link it to the network. Even for conventional rotary generators it may be preferred to use an asynchronous or induction generator (with a suitable inverter) and then use a DC linked inverter to connect the power source to the network. The power electronics can also be used to control the generation of reactive power to meet the needs of the load.

3.4.1. Inverters

Inverters for utility connection can be broadly classified into two types: single-phase inverters and three-phase inverters. Detection of islanding (see Section 3.4.2) is much easier in a three-phase than a single-phase inverter, although inverters that are rated at a power below 5 kW are mostly connected to single-phase networks.

Most modern inverters which are used for connection of small generators employ controlled power switches (e.g. MOSFET, IGBT), and generally use pulse width modulation (PWM) control signals for producing an AC output. Previous thyristor based systems were turned-off using the 'zero crossing' of alternating current from the mains. In either case, inverters need to synchronise with the utility network and cease to energise the utility network on islanding.

Fig. 2 shows a schematic structure of a self-commutated PV inverter with a low frequency transformer to provide isolation from the grid. In order to reduce the weight and the price, a high frequency transformer is also sometimes used but it is uncertain whether DC injection can be maintained sufficiently low to satisfy the most stringent regulations.

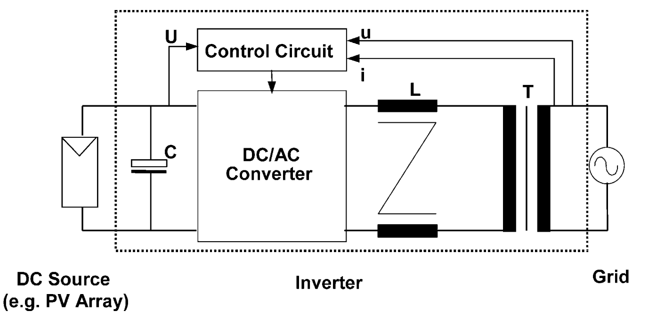

Fig. 2. Schematic diagram of an inverter.

3.4.2. Utility integration issues

The connection of micro-generators to the public supply system has been an issue under much discussion over the recent years, and the progress made in resolving the technical and legal issues is likely to play a significant role in the development of a similar framework for the microgrid.

Although there are differences in these grid-connection procedures presently applied in different countries and by different utility companies, there are many common attributes. The network operator will generally require that the connection of a generator conforms to the relevant codes of practice and engineering recommendations, particularly with respect to safety. There must be adequate protection for both the supply network and the inverter. The power quality will also have to be sufficient not to affect adversely the utility equipment and other users connected to the network.

The main technical barrier for utilities has been the issue of 'islanding' where the power to a local area of the electricity network could potentially be maintained live by a distributed generator, even where the main supply is switched-off or lost in a fault. Alternatively, islanding can be considered as the condition in which a portion of the utility system, which contains both load and generation, is isolated from the remainder of the utility system and continues to operate.

The commercial terms for payment for exported energy are contained in the Tariff Agreement which varies from country to country and electricity company to electricity company. In a number of countries (for example, Germany, Spain and Switzerland), the utilities are obliged by law to pay a premium price for PV electricity. Further information on year-by-year changes is available from an annual survey published by IEA Task 1.

One forum which has been involved in the study of these problems is the Task 5 of the Photovoltaic Power Systems (PVPS) Programme of the International Energy Agency.

Table 4
Summary of the current technical and regulatory framework for the connection of small generators in the UK

Authorisation procedure	Installations need to be agreed with the local Distribution Network Operator (DNO). For larger units the DNO may require on-site commissioning tests and may also want the opportunity to witness the commissioning tests. However, the use of a type approved inverter for smaller units greatly simplifies the process. A connection (operating) agreement also needs to be in place with the local DNO and an appropriate supply (tariff) agreement with an electricity supplier if any export settlement is required
Engineering Guidelines	The original Engineering Recommendation governing embedded recommendation G59 and G59/1 was supplemented by G77 and G77/1 (2002) which addresses single phase generators up to 5 kVA. G77 has been superseded recently by a broader based G83. The mandatory protection features in G77 and G83 include disconnection of the inverter based on over and under voltage, over and under frequency, and a recognised loss of mains technique, such as vector shift or frequency shift. Active techniques that distort the waveform beyond harmonic limits or that inject current pulses are not allowed
Legal and tariff situation	Electricity suppliers are not obliged to buy electricity produced by a small distributed generator. Tariffs paid for electricity fed into the grid vary with supplier, however, the rate is normally less than that for imported units. Some suppliers now offer the same price. A separate meter for energy fed into the grid is required

A number of reports have been published and Engineering Guidelines have been prepared to facilitate these procedures. The general technical, legal and commercial aspects of regulations in the UK is summarised in Table 4. The situation in several other countries can be found in the IEA Report [19]. A possible connection scheme for photovoltaic generators is shown in Fig. 3.

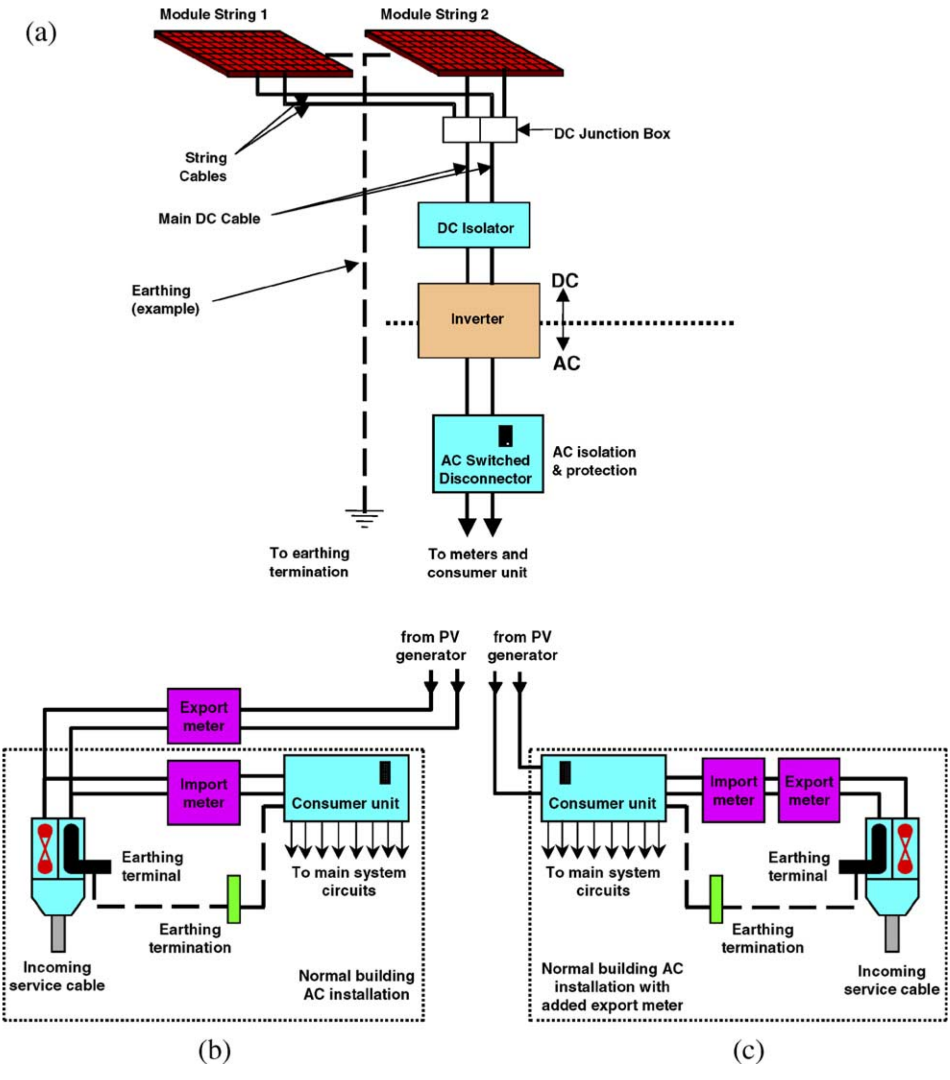

Fig. 3. A diagram showing the connection of a small generator in a domestic installation on the example of a PV system ([7], Chapter IIIc-1). (a) The generator. (b) Connection scheme of the meters and consumer units suitable for countries (notably Spain) where all PV power is exported to the network. (c) An alternative scheme where only the excess power not used on-site is exported to the network. The case (c) is common, for example, in the UK, and a PV generation meter is then often installed on the AC side of the inverter. Combined export/import meters are now also available.

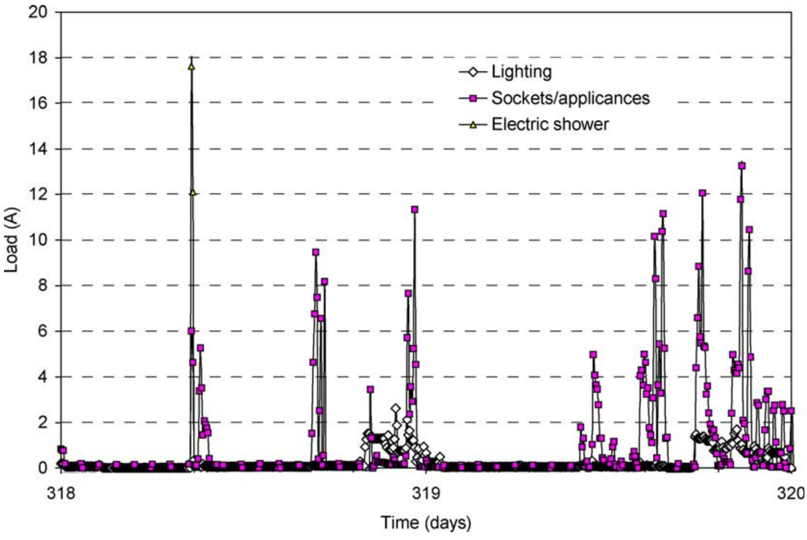

Fig. 4. The typical electric load profile of a household over two days.

3.5. The domestic load

The profile of electricity consumption and heating requirements of households are discussed in detail in Section 4. These smooth profiles are obtained by averaging over many households, and are applicable to sufficiently large microgrids. For smaller networks, peaks due to individual appliances will appear in the profile, presenting a challenge to the control of the power balance in the microgrid. Typical load profiles which

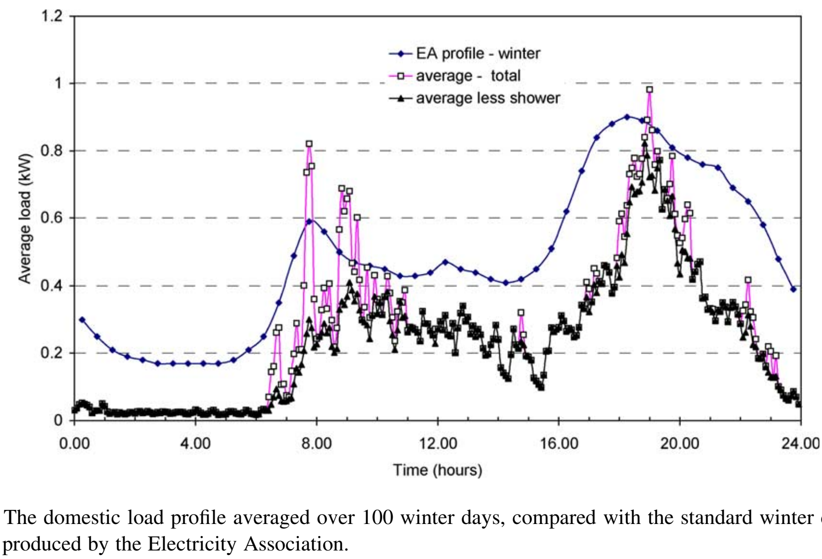

Fig. 5. The domestic load profile averaged over 100 winter days, compared with the standard winter domestic profile produced by the Electricity Association.

are likely to arise have been studied by monitoring the actual consumption of a household over the period of several months.

We have seen in Section 2 that the power profile of the demand is an important consideration for the control of the microgrid. Fig. 4 shows the electric power consumed by this household over a typical day. To examine the averaging or 'diversity' effect, Fig. 5 shows the average load profile averaged over 100 days. Whilst only an approximate representation of the load profile of 100 households during one day, this profile is now seen to be relatively smooth, and approaching the standard domestic load profile quoted by the former UK Electricity Association. The electricity consumption by the electric shower—which represents the largest load (7 kW) of this household—remains visible, and a larger average (corresponding to a larger microgrid) is needed for it to 'blend in' to obtain a smooth profile overall.

In a microgrid with energy storage, short-term fluctuations in energy balance are compensated by the battery. It will be seen in Section 5 that the natural design procedure for microgrids which contain photovoltaic arrays provides for sufficient storage to cover variation in the hourly demand during one day. The fluctuations in the daily energy consumption then become important and, as seen in Fig. 5, these are appreciable at the single household level. The total fluctuations in daily electricity consumption (Fig. 6) in a larger microgrid, however, will be less significant. Adopting a similar approach as for the power fluctuations, an estimate has been obtained by taking the average of the total energy demand over a number of days, and considering the relative fluctuations δ, where

$$\delta^2 = \frac{\langle E_n^2 \rangle - \langle E_n \rangle^2}{\langle E_n \rangle^2} \tag{3.2}$$

where E_n is the energy consumption over n days. It is seen from Fig. 7 that δ can be represented by the square root dependence

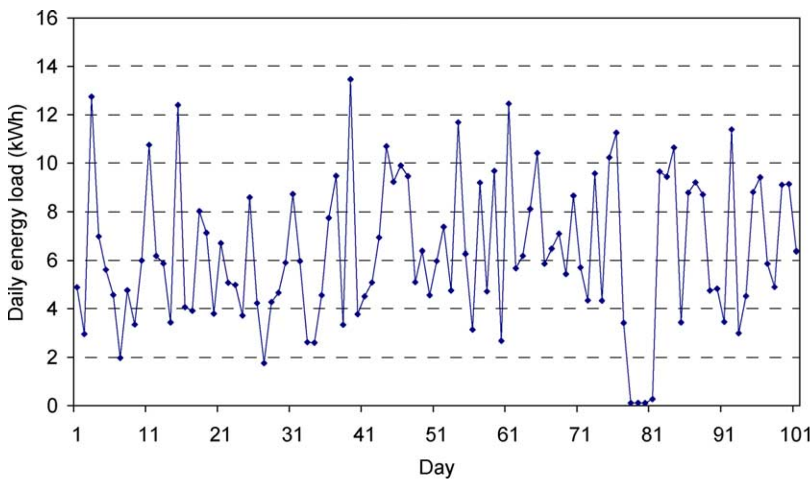

Fig. 6. The daily household load as a function of time.

$$\delta \cong \frac{1}{\sqrt{4.655n}} = \frac{0.46}{\sqrt{n}} \tag{3.3}$$

as one would expect from the law of large numbers for n independent loads. Although further work is needed to substantiate the validity of (3.3) in general, it is seen that the random variations in the electricity demand in a microgrid with over hundred houses are small, at the level of a few percent. Further work is also required, to characterise regular variations over, for example, weekends and public holidays, which have not been singled out here for a special analysis.

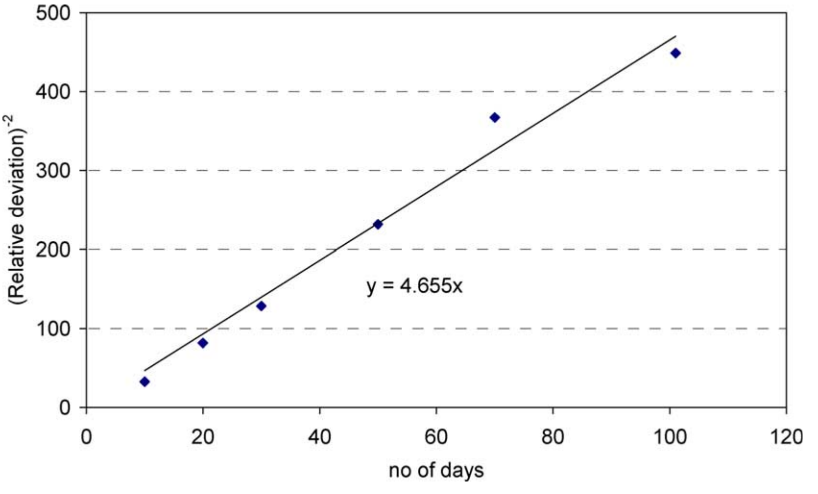

Fig. 7. The inverse square of the relative deviation as a function of the number of days of load, approximating the size of the microgrid.

4. Modelling energy consumption in buildings

4.1. Introduction

This Section focuses on the modelling of the load profile as a function of time for the housing sector. This has been grouped into two categories:

1. Domestic appliance electricity consumption load profile.
2. Space heating and hot water load profile.

The electricity profile is used to validate the methodology as a comparison is available with the average domestic electricity profile, available from the former Electricity Association. The validated methodology is then used to produce a heating energy load profile (space heat and hot water) which forms the basis of the sizing calculations in Section 5.

The energy consumption by domestic appliances has a high correlation to people's customs and may be slightly influenced by season. The electricity load profile depends

Table 5
Domestic appliances

Brown goods	Electric consumer goods-TVs, VCRs, music centres and satellites and cable TV equipment
Cold appliances	Refrigerators, freezers and combined fridge-freezers
Cooking appliances	Electric ovens, electric hobs, kettles, microwaves and small cooking appliance
Wet appliances	Washing machines Tumble dryer Dishwashers
Cleaner	Vacuums
Miscellaneous 1	Irons, electric showers, PCs and other office equipment
Lighting	Lights
Miscellaneous 2	Central heating pumps

mainly on the household size and occupancy pattern. Sufficient daylight in summer was considered when calculating electricity lighting load. Space heating load profile mainly depends on the weather conditions, building characteristics, occupancy pattern, income level, etc. Domestic hot water depends on the household size and on the occupancy pattern.

The United Kingdom has a population of 57 million (1996) and a total of 23.5 million households. The model of electricity load profile is based on the household size of three—the average household size. [20] Space heating load calculation is based on a typical UK three-bedroom house.

4.2. Domestic electricity load profile

The domestic appliances are listed in Table 5. Lighting and central heating pump electricity consumption varies in winter and summer. The common UK occupancy scenarios are shown in Table 6. Table 7 indicates the lights on/off pattern for each occupancy scenarios in summer and winter. The statistical data from UK Electricity Association Load Research have been analysed, and the national average electricity load profiles for the different household size have been generated. The load profile for the urban group can be calculated using the equation:

$$\mathrm{Load}_{\mathrm{urban}} = \sum_{i=1}^{5} F_i \mathrm{Load}_i \tag{4.1}$$

F_{i} is the percentage of UK national household in the size category (see Table 8), $i = 1$–5 is the UK household size, and $\mathrm{Load}_{\mathrm{i}}$ is the hourly load profile of each size of household.

Table 6
The occupancy styles for a three-person family

Scenarios	Type	Unoccupied period
Scenarios 1	Part time working morning session	9:00–13:00
Scenarios 2	Full time working	9:00–18:00
Scenarios 3	Part time working	9:00–16:00
Scenarios 4	Not working	N/A
Scenarios 5	Part time working afternoon session 1/2	13:00–18:00

Table 7
The electric lighting patterns

Hour	Winter					Summer				
	S 1	S 2	S 3	S 4	S 5	S 1	S 2	S 3	S 4	S 5
1	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off
2	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off
3	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off
4	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off
5	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off
6	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off
7	On	On	On	On	On	Off	Off	Off	Off	Off
8	On	On	On	On	On	Off	Off	Off	Off	Off
9	Off	Off	Off	On	On	Off	Off	Off	Off	Off
10	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off
11	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off
12	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off
13	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off
14	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off
15	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off
16	On	Off	On	On	Off	Off	Off	Off	Off	Off
17	On	Off	On	On	Off	Off	Off	Off	Off	Off
18	On	On	On	On	On	Off	Off	Off	Off	Off
19	On	On	On	On	On	Off	Off	Off	Off	Off
20	On	On	On	On	On	On	On	On	On	On
21	On	On	On	On	On	On	On	On	On	On
22	On	On	On	On	On	On	On	On	On	On
23	On	On	On	On	On	On	On	On	On	On
24	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off

4.3. Heating load profile

The hourly heating load profile for the UK coldest month (January) was simulated using the thermal simulation tool developed at the Martin Centre. The simulation for different house types (see Table 9) has been performed. The building information is listed in Table 10. The heating load profile is shown in Fig. 8.

Table 8
Percentage of UK household size

1 person	2 person	3 person	4 person	Five person
26%	39%	29%	5%	1%

Table 9
Typical 3-bedroom house types

3-Bed flat	3-Bed semi-detached	3-Bed detached	3-Bed mid-terrace

Table 10
Building information used in the modelling

Climate	UK Kew 67 Solar: beam, horizontal diffuse Air temperature
Dimension	Length, 5 m; width, 8 m; height, 2.7 m for a house (2 storey). Length, 10 m; width, 8 m; height 2.7 m for a flat
Orientation	South–north
Windows	South window 6.5 m^2; north window, 5.4 m^2 (double glazing)
Thermal mass	Medium

4.4. Domestic hot water

The domestic hot water (DHW) system is usually designed to provide approximately 50 l per head per day. The energy used for domestic hot water depends on many factors such as the required water temperature (currently, the average is 50 °C), the amount required per person, and the household size. The load profile will depend on the operating schedule, which depends on the family occupancy pattern. The method is similar to the electricity load profile calculation. The average daily DHW for a 3-person household has been calculated and is shown in Fig. 9.

4.5. Validation

The space heating load profile was produced using the thermal model developed at the Martin Centre. The model has been validated by the simulation software Espr [21].

There is a relatively close agreement between the modelled and statistical data for the 3-person profile (see Fig. 10). The correlation coefficient for these two profiles is 0.7. The electricity profile for a 3-person household has been compared with the UK national statistical data (see Fig. 11). From the figure we can see that the electricity consumption

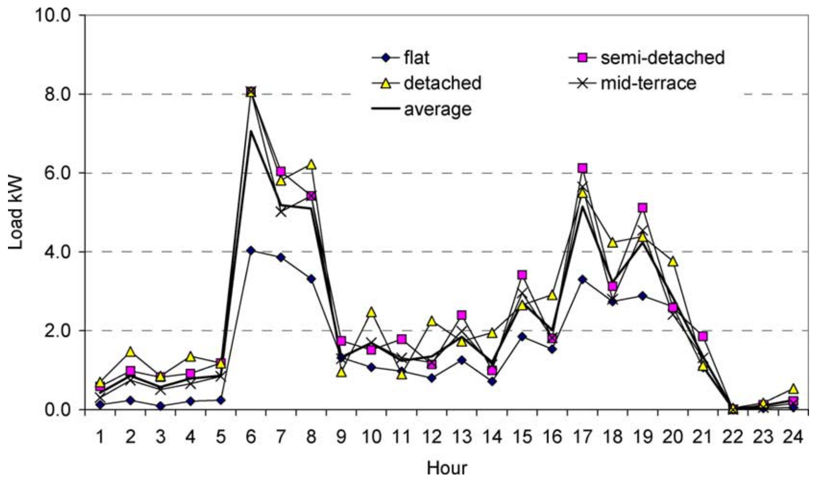

Fig. 8. The heating load profile in winter.

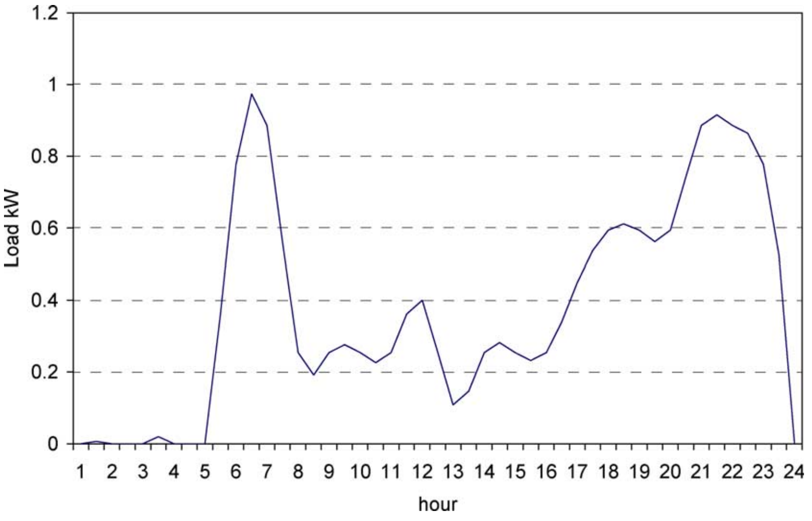

Fig. 9. Daily DHW demand of a 3-person household.

given in the national statistical data is higher than the modelled one. This is probably because the national statistical data include a proportion of electricity heating during the night. However, the modelled data are just related to the domestic appliance.

4.6. Discussion

The method of predicting the electricity profile is based on five approximate scenarios. Since the different houses have different daily load shapes, the peaks in the aggregate load shape will not be so pronounced as for each individual house. When the five approximate scenarios are aggregated, the load profile shape appears as a relatively smooth curve throughout the day. When compared with the UK national statistical data, this averaged curve shows a good agreement. The creation of a set of demand models corresponding to actual pattern using stochastic techniques should be the subject of a future study.

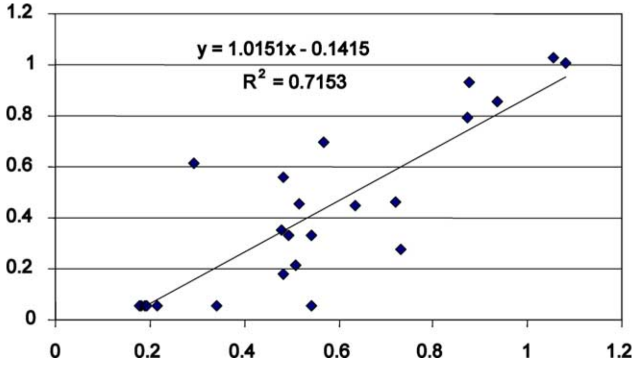

Fig. 10. Correlation between the model and national statistical data for a 3-person household.

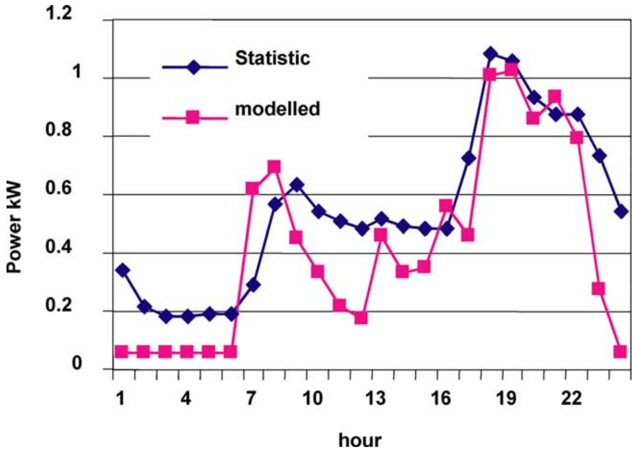

Fig. 11. Comparison of the modelled electricity load profile and the national statistical one.

The space heating load profile is the result of a simulation result for a 3-bedroom house/flat specified by a typical building information and UK Kew 67 climate data. The model itself can simulate different sizes and types of buildings.

5. An example of sizing: microgrids powered by photovoltaics and micro-CHP

5.1. Introduction

If operating stand-alone or isolated from the main public network, the energy generated within the microgrid must equal the consumption. This energy balance can be considered over a range of time scales. The energy balance over very short time scales—the power balance—was discussed as part of the microgrid control in Section 2. This Section considers the energy balance over longer periods of time: the hourly energy balance during one day, and the daily balance over the period of one year. The requirements of energy balance over these two disparate periods of time have different impacts on the design and configuration of the microgrid. Central to this analysis is the issue of energy storage which needs to be provided to bridge any imbalance between the generation and load, and the necessity that sufficient energy be available over time scales which cannot be bridged by storage.

As an illustration let us suppose that there is a systematic imbalance between the energy generated and consumed in the microgrid during one day. Over a period of weeks or months, this imbalance will increase by a sizeable factor, producing a large energy deficit. To cover this deficit, the energy storage would need to be unrealistically large. For this reason, the arguments developed in this Section will be based on the requirement that the mean daily imbalance in the microgrid is zero. We shall show in Sections 5.2 and 5.3 that this requirement can be achieved by an appropriate composition of generators in the microgrid—for example, by a suitable 'mix' of micro-CHP and photovoltaic arrays.

It is unrealistic to expect an exact hourly balance between energy produced by these sources and the user demand, and this needs to be supplied by energy storage. The size of the battery can be estimated from the average generation profile during the day (Section 5.4).

5.2. The methodology

On a daily basis, the energy balance in the microgrid powered by several generators can be written as

$$D \leq \sum_n E_n \tag{5.1}$$

where D is the daily electricity demand and E_n is the energy produced by generator n. For renewable generators, the energy production is closely linked to resource availability, and can be approximately assumed to be equal to the product of the daily resource energy R_n and the rated power P_n the generator:[2]

$$E_n = P_n R_n \tag{5.2}$$

Although approximate, Eq. (5.2) has had much success in practical use [22]. For an improved accuracy, the efficiency P_n should allow for the dependence on operating conditions.

Eq. (5.2) can be illustrated on the example of the daily output from the PV generator. In this instance, the resource energy is often quoted as Peak Solar Hours (see Section 3.2) and the efficiency is equal to the peak power of the array under the irradiance of 1 kW/m^2 at standard conditions. In the case of wind turbines, the rated power is a suitable average of the product of the power coefficient and the swept area by the rotor; the resource energy R is the mean daily wind energy per unit area.

A different reasoning needs to be applied to micro-CHP. Let us suppose that a single type of micro-CHP generator is employed which produces electricity and heat with efficiencies η_e and η_h, respectively. The overall energy efficiency is thus $\eta_e + \eta_h$. Each micro-CHP generator supplies heat to the household where it is installed but feeds the electricity to the network of the microgrid. If—in households where it is installed—the micro-CHP generator is the only source of heat for space heating and hot water, it must cover the total thermal energy demand Q of the household. The electricity produced by this generator is thus $\eta_e Q/\eta_h$. Hence:

$$E = \frac{\eta_e}{\eta_h} Q \tag{5.3}$$

One can, therefore, write (5.1) in the concise form

$$D \leq \sum_n P_n R_n \tag{5.4}$$

[2] For some generators (for example, wind turbines), 'rated power' has a somewhat different meaning than in the power generation industry. See below for further details.

where the 'driving forces' R are the renewable resources or heat demand in the case of micro-CHP, and P is the rated power in the case of renewable generators and the ratio of efficiencies in the case of micro-CHP.

If sufficient energy is to be available for stand-alone operation, Eq. (5.4) must apply at any time of the year. In practice, it is usually applied to seasonal or monthly averages of R's. The system of Eq. (5.4) then represents a set of equations which, subject to economic constraints, defines the composition of generators in the microgrid.

5.3. Daily energy balance in a microgrid

The above formalism has been used in the past in the design of hybrid photovoltaic/wind energy systems [23], and will be applied here to microgrids consisting of photovoltaic and micro-CHP. For two types of generators, Eq. (5.4) have a simple graphical solution for the rated powers P_{PV} and P_{CHP}, as shown in Fig. 12. Here, the points in the Cartesian plane corresponds to the configurations (P_{PV}, P_{CHP}) of the hybrid system; those that satisfy the inequalities (5.4) lie in the shaded area of the plane, bounded by two lines determined by the two inequalities in (5.4).

It follows from the linear programming theory that the optimum configuration lies in one of the vertices of this region. Thus, there are three possible solutions: a micro-CHP unit or PV array alone, and a combined system. We shall see that the combined system is likely to be the preferred solution as the PV array size would need to be very large to supply all the electrical demand on a winter day. Similarly, the micro-CHP electrical output (and, therefore, the overall size) would need to be large if it were to supply all the electricity during summer when the heat requirement is low. We thus have a convenient methodology which can be used to determine the required complement of generators in the microgrid.

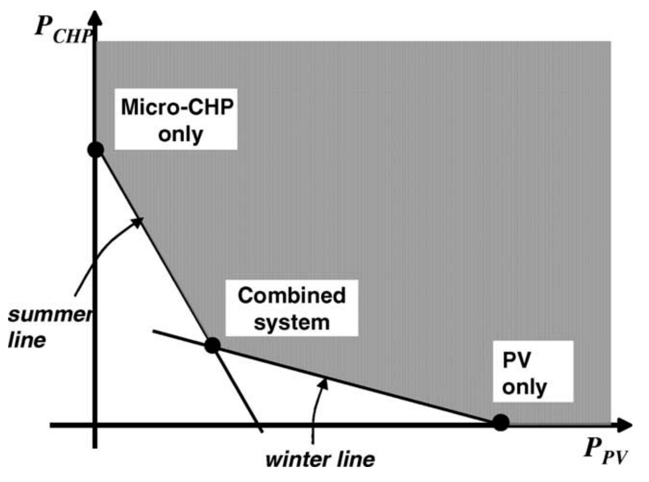

Fig. 12. A graphical solution of the energy balance method for a microgrid consisting of PV arrays and a micro-CHP.

To this end let us suppose for simplicity, that the microgrid employs a single type of micro-CHP generator. Eq. (5.4) then becomes

$$D \leq (\mathrm{PSH}) \sum P_{\mathrm{PV}} + \frac{\eta_{\mathrm{e}}}{\eta_{\mathrm{h}}} \sum Q \tag{5.5}$$

where $\sum P_{\mathrm{PV}}$ denotes the total size of the PV array in the microgrid, and the sums in the second term on the right hand side goes over all households with micro-CHP generators. Dividing (5.5) by the total number of households N

$$d \leq (\mathrm{PSH}) P_{\mathrm{PV}} + \frac{\eta_{\mathrm{e}}}{\eta_{\mathrm{h}}} Q \nu \tag{5.6}$$

where d is the average electricity demand of a household, P_{PV} is the average size of the *PV* array, ν is the fraction of households with micro-CHP generator, and Q now refers to the average full heating load.

To obtain numerical estimates, let us consider Eq. (5.6) for the summer and winter seasons only. Denoting by Q_{HW} the average domestic daily hot water demand and by Q_{SH} the space heating demand on a cold winter day, we then have:

$$d_{\mathrm{s}} \leq (\mathrm{PSH})_{\mathrm{s}} P_{\mathrm{PV}} + \frac{\eta_{\mathrm{e}}}{\eta_{\mathrm{h}}} Q_{\mathrm{HW}} \nu \quad d_{\mathrm{w}} \leq (\mathrm{PSH})_{\mathrm{w}} P_{\mathrm{PV}} + \frac{\eta_{\mathrm{e}}}{\eta_{\mathrm{h}}} (Q_{\mathrm{HW}} + Q_{\mathrm{SH}}) \nu \tag{5.7}$$

To obtain numerical estimates, the ratio $\eta_{\mathrm{e}}/\eta_{\mathrm{h}}$ of the electrical to thermal power was taken as l/3 as might be expected for a typical thermal engine (see Section 3.3). As fuel cells become available with time, this ratio might increase to 0.5–0.6. The first units on the markets, however, are likely to be configured for the ratio of electrical to heat demand of a typical household rather than of the microgrid, with a considerably lower ratio $\eta_{\mathrm{e}}/\eta_{\mathrm{h}}$. The effect of temperature on the output from the PV array as well as any inefficiencies in system operation have not been explicitly highlighted in the analysis but can be included without difficulty in the definition of the rated power of PV array, as discussed in Section 3. Mean daily solar radiation values from the European Solar Radiation Atlas [24] have been used. The input data are summarised in Table 11.

Table 11
Data used in the modelling

Quantity	Value	Abstract Units	Remarks
Q_{HW}	8.6	kWh	Martin Centre model (see Section 4)
Q_{SH}	58	KWh	Martin Centre model (see Section 4)
d_{S}	8.3	KWh	Electricity Association data
d_{W}	11.5	KWh	Electricity Association data
η_{c}	0.2		Estimate based on Section 3
η_{h}	0.6		Estimate based on Section 3
$(\mathrm{PSH})_{\mathrm{s}}$	5.1	KWh/m^2	South of England; panel inclination 40° facing South [24]
$(\mathrm{PSH})_{\mathrm{w}}$	1.1	KWh/m^2	South of England; panel inclination 40° facing South [24]

Table 12
Results of the study giving the sizes of the PV and micro-CHP generation capacity

PV array per household (kW_p)	ν (micro-CHP generators per household)
1.37	0.45

The results are shown in Table 12 and the full range of microgrid configurations determined from (5.7) depicted in Fig. 13. It is seen that the optimum size of a PV generator suitable for an average house in combination with micro-CHP is about 1.4 kWp. It is also interesting to note that, as long as the heat output from the micro-CHP generator is sufficiently large to provide the heating needs of the house, it does not enter into the configuration of the microgrid. The relevant quantities are the efficiencies η_e and η_h and the 'penetration ratio' ν. For a typical housing estate, ν equal to about 0.5 is sufficient to supply all the electric power of the microgrid. Clearly, this is determined by the ratio of the winter heat demand (67 kWh/day) to electricity demand (11.5 kWh/day) of the typical house. Allowing for the ratio of the heat to electrical efficiencies of the micro-CHP, we obtain a roughly twice the daily electrical energy output than is consumed in the house. In a microgrid this electricity can be distributed among the users in the microgrid. If the micro-CHP units are installed individually without integration, the surplus electricity must be exported to the utility. Alternatively, a micro-CHP unit with a lower value η_e/η_h should be installed which does not benefit from the optimum efficiency of electricity generation. For a larger ν, of course, the power can be exported to the public network or a lower number of units can be installed. When fuels cells become commercially available, for example, the ratio of households that need to install this type of micro-CHP can be reduced to about 15%.

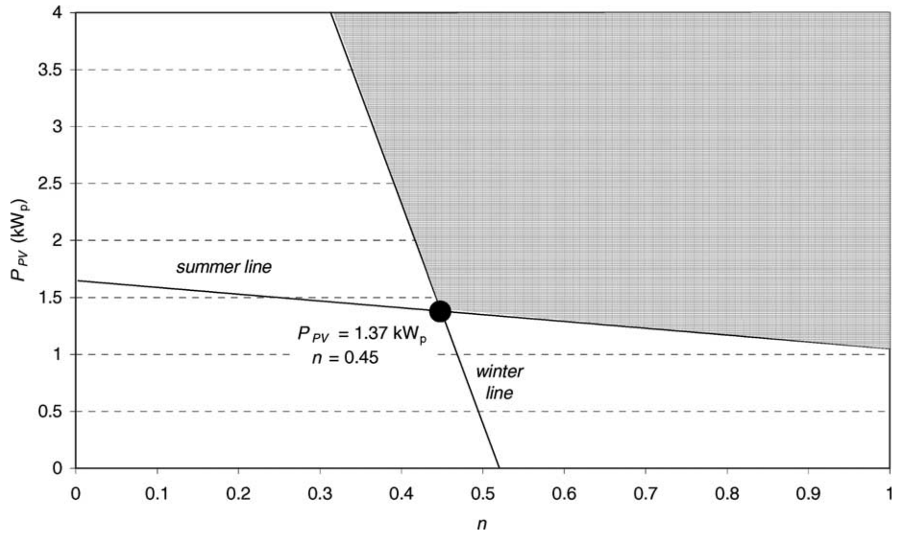

Fig. 13. Possible microgrid configurations for the parameters shown in Table 5.1. Configurations in the shaded region generate sufficient energy to supply load throughout the year. The configuration shown by point represents the optimum system.

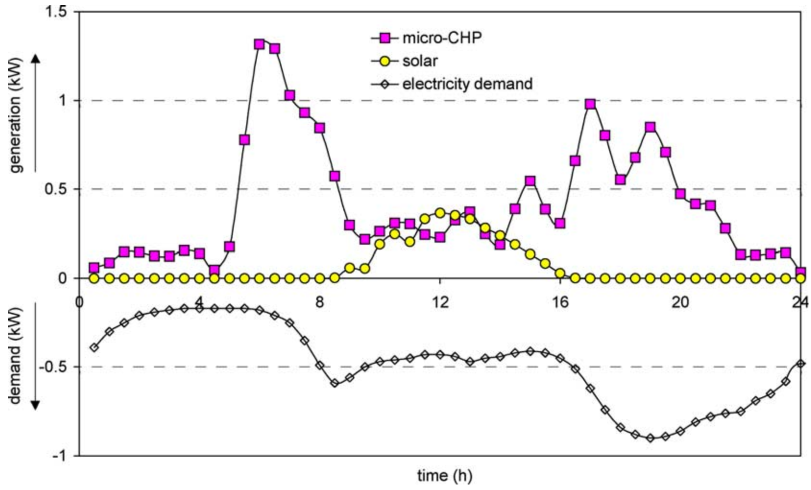

Fig. 14. The daily generation and load profile during a typical winter day.

5.4. Hourly energy balance. Energy storage

We now turn to the energy balance during one day. The basis for this analysis will be average profiles of the electricity demand available from the former Electricity Association and average generation profiles by the micro-CHP and the photovoltaic array. The former is assumed to be proportional to the average heat demand Q and given by $\nu\,(\eta_e/\eta_h)\,Q$, where Q consists of space heat and hot water demand, as described in detail in Section 4. The irradiance during a typical day with daily total solar irradiation shown in Table 11 was obtained from the measured data at the STaR Facility, University of Southampton [25].

The results are summarised in Figs. 14–17. Power generation and demand profiles over typical days in summer and winter are shown in Figs. 14 and 15, using system

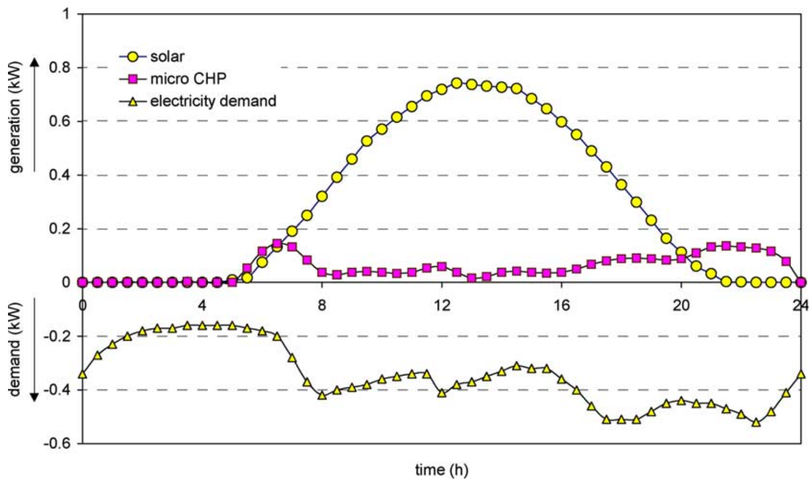

Fig. 15. The daily generation and load profile during a typical summer day.

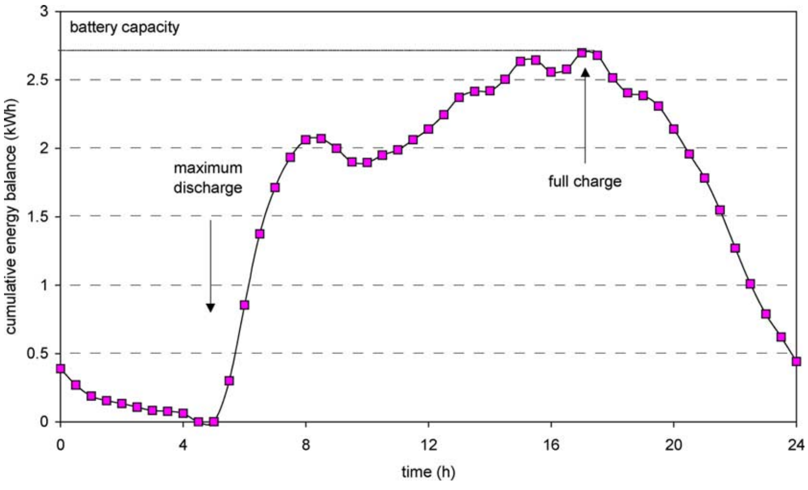

Fig. 16. The cumulative energy balance per household during a typical winter day, illustrated on the energy stored in the battery during the day. This graph shows that a battery of about 2.7 kWh is needed to cover the mismatch between generation and load.

configurations discussed in Section 5.3. Fig. 16 shows the cumulative energy balance during a typical cold winter day, plotted as the energy that would need to be stored to maintain electricity supply. It is seen that, in this case, a relatively modest energy storage of approximately 2.7 kWh would be needed. Fig. 17 shows the cumulative energy balance for a summer day. It is seen that the requirements for energy storage estimated for winter and summer days are almost identical.

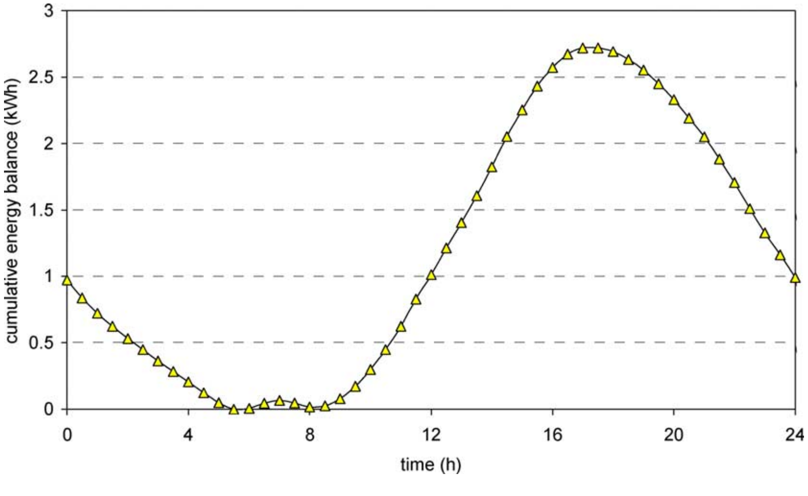

Fig. 17. The cumulative energy balance per household during a typical summer day. It is seen that a similar battery size (2.7 kWh) will cover the mismatch between generation as on a winter day.

5.5. Security of supply

5.5.1. Introduction

The security of supply in a traditional power system is determined principally by the likelihood of equipment failure. In microgrids which are powered by renewable sources, resource availability becomes an additional issue.

The close proximity of generators and load in a microgrid should improve both efficiency and reliability since there are fewer items of plant between source and load. Also, since there is expected to be a relatively large number of small generators this should help improve the reliability. Since there are unlikely to be overhead transmission lines, lightening and storm damage should not be a problem. It is also worth noting that the area affected by a failure will be limited to the microgrid if it is internal and the microgrid may be isolated from failure outside. This avoids the type of problem seen recently in London where a single failure propagated across the system causing large scale blackout, with even more dramatic failures in North America. The diversity and number of generators should also make for improved reliability. The storage could also help cope with short term problems. There is uncertainty over the reliability of small machines as compared with large ones, but this may be offset by time to repair.

The principal consideration security of supply of a system designed by the average daily energy balance considered in Sections 5.2–5.4 is the likelihood of energy supply exceeding the load; an energy deficit can come from insufficient generation or from excessive demand. In a system that relies solely on the renewable energy resource, a high security of supply can only be achieved by installing a larger array and/or energy storage. The operator of the microgrid, however, has also other the options. It may be possible to make an arrangement with the local utility to trade the surplus and deficit of electricity to provide a back-up supply. In stand-alone operation, the micro-CHP units can be run over above the times necessary to provide the heat. To examine the extra cost, it is necessary to determine the energy deficit which is likely to be experienced with the two power sources considered in this Section. The deviation in demand from the average value was considered in Section 3.5. In a reasonably large microgrid (over a hundred houses or so), the energy deficit due to random daily fluctuations should be small (of the order of a percent or two of the total CHP generated electricity) and can be neglected.

As already noted in Section 3.5, however, a more accurate analysis is needed to examine separately regular events such as weekends and public holidays where correlated deviations from average occur in both the heat requirement and electricity consumption due to specific occupation patterns.

5.5.2. Photovoltaic generation

Solar radiation is the principal source of energy for the microgrid outside the heating season. Rather than consider the complexities of the full probability distribution of daily solar radiation, a sufficiently accurate estimate can be obtained by using the following

expression for the expected annual energy deficit ΔE_{PV} based on Gaussian statistics:

$$\Delta E_{\mathrm{PV}} = \frac{\sigma_{\mathrm{G}}}{2G_{\mathrm{d}}} E_{\mathrm{PV}} \tag{5.8}$$

where σ_{G} is the standard deviation of the distribution from the average daily solar radiation value G_{d}, and E_{PV} is the photovoltaic energy produced.

Using the solar radiation data for the period from the beginning of May to the end of September, the standard deviation σ_{G} has been found to be

$$\sigma_{\mathrm{G}} = 0.40G_d \tag{5.9}$$

The result (5.9) has been obtained using the measured 1997–1999 solar radiation data at Southampton [25]. The frequency distribution of the mean daily solar radiation data is shown in Fig. 18.

5.5.3. Micro-CHP

In addition to the occupancy pattern which is discussed further in Sections 5.4 and 5.5.1, the principal reason for fluctuation in the daily energy produced by the micro-CHP are likely to be fluctuations in temperature. A simple estimate of the energy deficit can be obtained by assuming that the energy required to heat the house is proportional to the difference in temperatures between the inside (T_{i}) and outside (T_{o}) the house. Assuming again Gaussian statistics, this leads to the expression for the expected annual electrical energy deficit ΔE_{CHP}

$$\Delta E_{CHP} = \frac{\sigma_T}{2\{\langle T_i\rangle - \langle T_o\rangle\}} \frac{\eta_e}{\eta_h} Q_{SH} \tag{5.10}$$

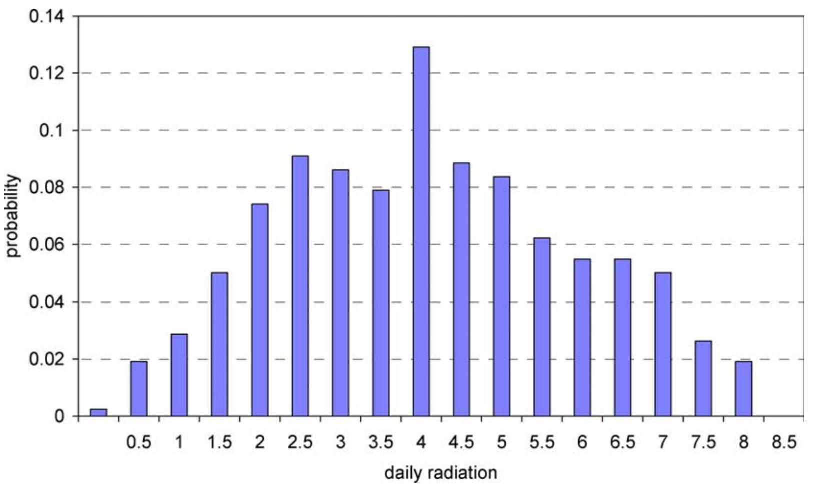

Fig. 18. The probability distribution of daily solar radiation (in kWh/m^2) in Southampton (UK) from beginning of May to the end of September during the period 1997–1999. Data from STaR Facility [25].

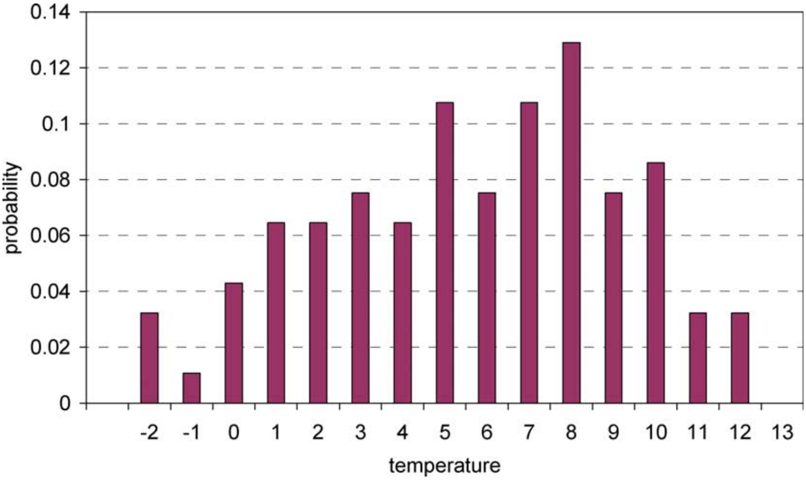

Fig. 19. The probability distribution of the average daily December temperatures (for Southampton, UK, in degrees Celsius) during the period 1997–1999. Data from STaR Facility [25].

where σ_T is the standard deviation from the average daily temperature and Q_{SH} is the space heat requirement. Eq. (5.10) should be considered on a monthly basis before the results for E_{CHP} are combined. For simplicity, the value of ΔE_{CHP} from an analysis of December data for Southampton for the period 1997–1999 [25], with the result

$$\sigma_T = 3.5C \quad \langle T_o(\text{Dec})\rangle = 6.12C \tag{5.11}$$

The frequency distribution of the average daily temperatures at Southampton is shown in Fig. 19.

5.6. Conclusions

We have shown, by considering the energy balance in a microgrid on typical summer and winter days, that a photovoltaic array of about 1.5 kW_p on every roof combined with a micro-CHP unit in every other house, will provide sufficient electricity to satisfy the demand of the households in microgrid. Energy storage of about 2.7 kWh per household is also needed to make this electricity available at the appropriate time of day. The micro-CHP ownership can be reduced to some 15% when fuel cells become available as a domestic CHP generator.

Although the size of the required energy storage is not large (it corresponds to three or four typical traction batteries) it can be reduced further by demand management. For example, by setting the washing machines, tumble driers and dish washers to run during the early morning or afternoon generation peak on a winter say, the required energy storage can be reduced by about 1.4 kWh. A similar result can be achieved by switching on non-critical loads during the PV generation peak on a summer day. A further reduction in the battery size (by some 1 kWh) is possible by making use of the energy stored in the hot water tank and in the fabric of the building. It follows from

the discussion in Section 2, however, that the battery capacity cannot be reduced without limit as some storage is likely to be needed to allow satisfactory control of the microgrid. Notwithstanding, no attempt has been made in this study to estimate this minimum storage requirement.

A microgrid powered by intermittent sources also has to make provision for below-average generation. For photovoltaics and micro-CHP, an estimate made in Section 5.5 shows that about 15% of additional electrical energy—which may come from the supplementary generation by micro-CHP or from the utility supply—needs to be provided for this purpose.

These factors have impact on the economics of the microgrids which is considered in Section 6.

6. Economic analysis of microgrids. Regulatory issues

A few definitions

- A ‘Deep Connection’ charge is when the connection charge includes all the associated costs of connection including any costs incurred at remote locations or at higher voltage levels.
- A ‘Shallow Connection’ charge is when the connection charge includes the cost of connecting to the nearest appropriate point in the network (i.e. does not include remote costs or cost incurred at higher voltages).
- A ‘Shallowish Connection’ charge will include some element as yet undecided of the cost of reinforcement incurred. These definitions may be more explicitly defined, or altered, following more detailed financial analysis of the potential impact.
- Black Start: restart time from fault or emergency shutdown.
- CI: Customer Interruptions
- CML: Customer Minutes Lost
- DG: Distributed generation or ‘embedded’ generation:
- DGCG: UK government Distributed Generation Coordination Group (www:distributed-generation:gov:uk)
- DNO: Distribution Network Operator
- DUoS: Distribution Use of System Charges
- ESQCR: Electricity Safety, Quality and Continuity Regulations 2002.
- Ofgem: The Office of Gas and Electricity Markets
- DTI: Department of Trade and Industry

6.1. Introduction

This section reviews the still limited literature on the economics of microgrids. Microgrids have a significant potential to reduce GHG emissions from household energy use and could therefore make a major contribution to reducing GHG emissions. Much of the debate in the UK has concentrated on micro-CHP installations, especially since the formation of the DGCG. This section considers the implications of the microgrids project

for the potential for widespread adoption of microgrid technologies in the UK. Barriers that have to be overcome if microgrids are to make a major contribution to the UK energy system are identified. It will briefly review the discussion about micro-CHP and the economics of distributed generation in the UK. It will then consider the economics of microgrids in the light of the findings of the microgrids project and raise some economic and institutional questions that will have to be overcome if microgrids are to be deployed on a large scale in the UK.

6.2. Micro-generation

6.2.1. General overview

The main technology under current consideration is small gas fired Stirling engines, sized to provide the required heat output, but which also provide electricity output in a domestic scale CHP installation. The heat requirements for a typical household imply that there will be a surplus of electricity, which is commonly assumed to be sold into the national electricity grid. The DGCG has identified considerable potential for micro-generation [26]: more than 1 million household hot water boilers are replaced each year in the UK, which could be replaced by CHP. They suggest a realistic potential of 400,000 micro-CHP units by 2010 and up to 10 million by 2020. There is also substantial potential in SMEs. Crozier-Cole and Jones [27] report 17 million gas-fired central heating boilers in Great Britain, with 1.3 million boilers sold/year, also indicating a large potential market for micro-CHP.

The prospects for photovoltaics are more difficult to assess. Based on the market data over the last 10 years which show an approximate 30% increase/year and a 0.8 progress ratio (20% reduction in cost per capacity doubling) [28,29] in 6 years there would be a 500% increase in installations, which could be expected to lead to a 40–50% reduction in costs of the PV installation. Given favourable tax treatment and regulatory regime, this rate of cost reduction could dramatically improve the economic position of PV cells in just a few years time.

The DGCG has produced a series of studies of various aspects of distributed or embedded generation. DGCG considers charging principles [30]. They identify five possible options for future charging regimes for connection and use of distribution systems.

Option 1. Status Quo (The Reference Case)
- Generators continue to pay ‘deep’ connection charges (including micro and small generators, with exemptions for ‘larger generators’)
- Demand continues to pay ‘shallowish’ connection charges
- All other reinforcement costs are met through DUoS, which is paid solely by demand (customers)

Option 2. Shallow generator connection, all reinforcement costs paid by load customers.

Option 3. Shallow generator connection cost, reinforcement costs being shared by all parties.

Option 4. Shallowish generator connection cost, reinforcement costs being shared by all parties.

Option 5. Shallowish connection charge for smaller generators, Site specific charges for larger generators.

Options 2–5 would require fundamental changes to the regulatory pricing structure for connection of embedded generators and a clear commitment from Ofgem as to how they will treat the funding in the current and future ‘price control’ periods. Currently, embedded generation has to pay ‘deep’ connection charges, which disadvantages embedded generation in comparison with large scale generators, who only pay a ‘shallow’ connection charge. Ofgem has now decided to proceed with ‘shallowish charging’ which includes payment for connection and reinforcement at one voltage level above that of connection.

DGCG looks at options for micro-scale generation [31]. It finds that domestic and other micro-scale generators would like a simplified charging mechanism and simple technical requirements for connection that allows them to connect to the networks easily and quickly, with transparent charging and payment systems. It suggests that the freedom of choice to become a customer-generator may itself be of great value to the customer. Key issues are:

- meter arrangements for measuring the domestic and other micro-scale generation output, export and import units and maximum demand;
- technical requirements for connection to the distribution network to enable ‘parallel’ operation;
- the connection charge;
- tariff mechanisms (via metering, profiles and fixed charges) for use of the transmission and the distribution system, selling domestic and other microscale generation exports and buying imported electricity.

Current standard consumption profiles do not cater for non-half-hourly metered generation and so either additional profiles or a cheap and appropriate form of half-hourly metering is required. A further problem is that the majority of domestic and other microscale generation would currently be ineligible for ROCs. It is now likely that micro-generators using PV and other renewables will be eligible.

There are also problems with the charging structure for distribution. The DNOs major revenue driver is from the DUoS charge on each unit distributed for suppliers. Large generators do not currently pay DUoS on their exports, whereas micro-generators would have to pay this. One possibility would be for a DNO to set an annual capacity charge (often called an entry charge in discussions) ACC to provide locational signals for demand and generation within a distribution network area. Combined with ACC charge could be a Generator DUoS charge (not currently paid on exports) to be levied by DNOs to support the cost of providing the distribution network to customers with other micro-scale generation to enable units to be exported (the generator DUoS is also part of Ofgem’s latest proposals for the next Distribution Price Control). These charges could be levied on suppliers who would pass them on to customers (in some form of their choosing). Ten possible options for metering are identified; as combinations of three different meter arrangements: single direction meter, bi-direction meter, import and export metering with existing load profiles or separate import and export profiles.

Choudhury and Andrews also consider payment mechanisms for micro-generation [32]. They conclude that half-hourly metering can be excluded as a route to a final payment mechanism. It is currently far more expensive than other viable options; it does not seem to deliver benefits to the system or to the micro-generator that can justify the cost

and there are no industry participants calling for half-hourly metering to be mandatory for micro-generation. They consider that the main realistic options for discussion are: to allow micro-generators to maintain their existing single direction meters with a generation profile or to insist on the installation of import–export multi-register meters.

DGCG looks at the business environment and market based opportunities for resolving some of the issues, which could co-exist alongside the existing RPI-X regulatory mechanism [33]. It argues that there is uncertainty of the regulatory process. It would be beneficial to provide DNOs with a clear long term approach to: measurement of the relative performance of DNOs; treatment of capital and operational expenditure and the relationship between them; performance based regulation. For treatment of DNO business costs, the regulatory regime currently (in 2000) agrees a cash settlement covering both capital and operating expenditure. There are merits of moving from an asset based regulatory framework to one which takes output performance into account. Opportunities for DNOs to provide extra services and hence obtain extra revenues might include:

(a) extra security
(b) shortening post fault restoration times
(c) more stable voltage (reduces fluctuations)
(d) higher fault level (dip reduction).

Another important set of possibilities is the creation of a local ancillary services market. Ancillary services can be defined as:

1. Security Services
   - Provision of network capacity
   - Provision of customer service improvements in terms of CI, CML, Worst served customer and Transient interruptions
   - Provision of Power Quality improvement in terms of voltage flicker, harmonics and protection operating times
   - Provision of voltage support
2. Ancillary Services
   - Provision of Reactive Power as a tradable commodity (i.e. not necessarily for voltage support locally)
   - Provision of Frequency Response
   - Provision of Reserve
   - Provision of Black Start

Crozier-Cole and Jones [27] consider the potential market for micro-CHP in the UK. They identify the following critical issues that will have to be addressed if micro-CHP is to be adopted on a large scale in the UK:

- Grid connection procedures and standards appropriate for a mass market.
- Product testing and field trials covering representative UK housing stock and occupancy types.

- Preparation of the delivery chain-skills for installation and service; actions to prepare UK workforce, e.g. an Installer Accreditation scheme
- Introduction of simplified metering, settlement and trading procedures to obtain maximum value from micro-CHP generation.
- Review of 28-day utility rule as a potential barrier to utility led Energy Service Companies (this rule effectively prevents energy providers signing long term contracts with retail customers).

6.2.2. Summary of regulatory issues and current regulation activities

It is apparent from the above survey of DGCG reports that, quite apart from the costs of installation of micro-generation, the electricity market in the UK is organised such as to present considerable barriers to the large scale adoption of micro-generation. Some key issues are summarised in DCGC [26]:

- Deep connection charges—Micro-generation currently has to pay deep connection charges, which large scale generators do not have to pay.
- High cost of participation in electricity markets—the current arrangements under NETA require considerable expense and expertise to make contracts to supply electricity to the grid. Currently, it is necessary to bilaterally agree a new contract if generation is to be installed. This penalises micro-CHP in particular, if an individual household is installing a micro-CHP unit. What is required is a standardised generation connection and Use of Supply agreement, that comes into force automatically upon connection.
- The network is built for uni-directional flows, with little active management—there are no simple arrangements for bi-direction metering or demand and supply.
- Lack of incentive for DNOs to connect small generators.

There are also engineering requirements, which have been addressed by the DGCG:

- G83 Connection Standard is now defined.
- A suitable interpretation of the Wiring Regulations has been developed.
- ESQCRs have been defined.
- Metering-BSC modification defined.

Ofgem is currently considering changes to the regulatory regime to address some of the charging issues. Ofgem is committed to moving from a deep to shallower charging regime, with shallow charging at EHV and shallowish at lower voltages. They are also considering price control mechanisms to provide more suitable incentives for DNOs [34].

6.3. Microgrids: the context of current government thinking in the UK

6.3.1. Registered power zones

The UK Office of Gas and Electricity Markets (Ofgem) in their documents [35] set out a proposal for ‘registered power zones’. This proposal follows extensive consultation within

the Industry and forms part of the innovation initiatives flowing from the ongoing work to encourage both distributed generation and the use of ‘renewable’ sources.

Whilst a registered power zone (RPZ) is as yet not defined in any detail, it is clear that Ofgem are considering something that must be innovative. The intention is for a DNO to register a defined zone in which innovative plant and systems may be used either to generate or control power flow. The financial incentives to set up and run such a zone are very attractive. Thus Ofgem hopes to persuade the DNOs to set up and operate such zones.

The outstanding issues, on which Ofgem are inviting views concern the application of industry standards particularly those pertaining to quality standard at consumers terminals. Derogation of some standards is likely to encourage innovation and so Ofgem is actively considering a move in this direction.

A report [36], in July 2003 set out a number of both short tem and longer term solutions to some of the connection problems. It is likely that any move to use these methods to establish a registered power zone would succeed in attracting the attractive connection terms.

The solutions considered by the report concentrate on preserving the network and many ideas are explored. Only in one area is ‘network splitting’ considered and the conclusions are not very positive. This was because it was only considered as a method of reducing fault level in an existing network. Power quality and short-term interruptions were seen as the disadvantages of a smaller network.

It is clear that the Working Group did not see any real benefits for a separated or loosely coupled microgrid. Areas of investigation were identified where work is required to identify the balance between reduction in fault levels and impact on customers.

6.3.2. The view of the electricity industry

The concept of a microgrid is not under active consideration by DNO’s for two major reasons:

- It is not in the interest of a DNO.
- The perceived benefits are not easily defined.

A DNO perceives its best interest is served by preserving its own network and hence the RPZ concept is acceptable. The RPZ allows financial incentives and may allow relaxation of ‘power quality’ standards, both seen as an attractive way forward. The notion of RPZs has not—quite deliberately—been defined very precisely. It is possible, however, to interpret the rules in a way that will allow the concept of a microgrid.

A microgrid may be of any size, as may an RPZ; hence a small RPZ could be a large microgrid. The degree of ‘connection’ to the utility network is also undefined and can therefore encompass the loose coupling envisaged of a microgrid. A DNO owned and operated microgrid is, therefore, entirely possible whilst not being seen as threatening the network.

Whilst not seen as a primary initiative, a microgrid could operate within an RPZ if it can be seen as possessing advantages. It is thus the advantages, technical, political and commercial, which must be carefully set out as the argument for the setting up of a microgrid. The only other alternative is the promotion of a completely new, private

and independent microgrid, which whilst possessing some advantages is unlikely to attract DTI incentive funding. It is likely therefore that the thinking on microgrids should take two directions:

- As a very specific RPZ.
- A quite small network (up to several megawatts).

6.4. Economic analysis of microgrids

There are several potential economic benefits of microgrids:

- Reduced transmission and distribution costs and energy losses.
- Potentially total higher energy efficiency.
- The small scale of individual investments reduces capital exposure and risk, by closely matching capacity increases to growth in demand.
- The low capital cost potentially enables low-cost entry into a competitive market.

The micro-generators considered in this paper also provide savings through the higher efficiency of energy provision. When integrated into a microgrid, the generated electricity can be shared among the consumers, obviating the necessity to export power to the public network at a lower price. There are other potential benefits for the electricity system in security and ancillary services from distributed generation, outlined from DGCG [33] above.

As with most other renewable energy sources, the cost of electricity generated by photovoltaic generators is dominated by the initial capital outlay. The cost to consumer is therefore dependent heavily on the financing terms, and the requirements of short term repayment schedules put these energy sources at a disadvantage. In particular, the financing of photovoltaics considered here reflects the increasingly common perception of photovoltaic arrays as a building component and can therefore be paid for over the same term, by a 25 year mortgage. An indication that longer term investment is possible comes from a number similar projects in the UK (for example, the Woking Energy System and the Southampton Geothermal Project) as well as the experience with building integrated photovoltaics in Germany and Japan.

It is instructive to compare the different integration strategies for micro-generation in terms of three ‘Scenarios’. Scenario 1 considers micro-CHP units installed individually, without integration into microgrids; there is no photovoltaics and no energy storage. Scenario 2 describes microgrids consisting of micro-CHP and battery only, designed to supply all heat and electricity in winter. In summer, the household buys the electricity shortfall from the main utility. Finally, scenario 3 describes the full microgrid consisting of micro-CHP, PV and storage, and capable of stand-alone operation, as analysed in Section 5.

Electricity generation, purchase and export in the three scenarios is summarised in Table 13. The amount of energy exported in Scenario 1 has been estimated from the comparison of the micro-CHP generation and demand in Section 5. The total household consumption in all three cases is assumed to be equal to the UK average of 3300 kWh per

Table 13
Electricity generation, purchase and export, summarised in the form of three Scenarios (in kWh per household per year)

Scenario		1	2	3
Micro-CHP generation	With heat recovery	2700	2064	2064
	Without heat recovery	0	0	505
PV generation		0	0	1236
Electricity export		900	0	0
Electricity purchase		1500	1236	0

annum, although the electricity generated by the household may exceed this value. In scenario 1, this is due to the fact that there is no energy storage to accommodate the mismatch between generation and load. In scenario 3, on the other hand, electricity additional to the expected values has to be generated to provide the required security of supply. Both these surpluses can be removed by installing extra storage or extra generation, at an additional cost.

Scenario 1 describes the situation when DCHP units enter the marketplace, which is considered here to occur in the near term. The results are broadly consistent with the findings of the DGCG and EA Technology reports [37,38]. When considering the cost of the micro-CHP it is usual to include only the additional cost to installing an efficient central heating boiler. If a net metering arrangement can be negotiated with the electricity supply utility, the saving in electricity can reach 50% of the electricity bill [37], representing a simple payback period of some 4 years.

If the electricity supply company is less forthcoming and offers a tariff in keeping with the bulk electricity price, the reduction in household electricity costs become less advantageous to the householder. This extends the payback period to some 5–6 years. The latter situation is likely to prevail once DCHP generation becomes established in the market and rigorous economics is applied to the electricity trading arrangements.

At this point, there is a likely to be little incentive on the part of the householders to take the next step and integrate micro-CHP units into microgrids. This is because the electricity cost to the householder under the microgrid scenario 2 is likely to be similar as under scenario 1 with no net metering where no action needs to be taken by the householder aside from the purchase and installation of the micro-CHP units.

The economic balance is likely to change as the penetration of micro-CHP (or PV generators) approaches the limit which can be tolerated by the distribution system. As the costs incurred by the electricity distribution companies to connect intermittent embedded generators rise, the economic environment is likely to tilt towards the microgrid scenarios 2 and 3. Scenarios 3 represents the more environmental alternative but are only likely to compete as a serious alternative if PV prices fall, or a government subsidy is available. We estimate that a reduction in PV cost of some 50% is needed to make the electricity cost in the full microgrid (scenario 3) competitive with the current electricity cost.

The above analysis applies to countries (such as UK) which have a comprehensive electricity supply network. In the developing countries with a poor electricity supply

system, or in rural locations in countries with a low population density (such as Australia) the microgrid scenarios may be the preferred solution at a much earlier stage. Many examples already exist of single stand-alone PV, wind or hybrid systems, or small networks of these generators which are already now cheaper than extending the electricity supply network.

6.5. Where do we go from here?

The analysis undertaken in this paper has shown that the electricity demand in a microgrid can be supplied by micro-CHP generators with penetration ratio of one for every second household, together with a photovoltaic array of about 1.5 kWp and energy storage corresponding to about 2.7 kWh per household (four industrial lead-acid batteries). This would then deliver an energy service independent of the grid network. As has been indicated, the economics of central heating boiler replacement with micro-CHP units is already quite favourable. If an installation and maintenance infrastructure can be developed, there should be a mass market for micro-CHP, which will both bring down costs and raise the public profile of these technologies. This would require firms with expertise in installation and maintenance, together with large scale manufacture and sales activities. These considerations suggest that a new type of firm—an energy service company with expertise in energy saving measures, supply and demand contracting, renewables and microgrids may be necessary to exploit and develop the new market structures.

A supportive regulatory structure is also essential. The ‘public profile’ is very important. Historically, new technologies have always faced economic and institutional barriers and only some technologies ‘take-off’. If there is a strong reason for society to pursue microgrids, these issues have to be addressed and institutions/economics changed through policy to make it happen. This requires not only a supportive public environment, but active policy and commercial support. Given that climate change is now a major element of energy policy, this can in principle happen, but a rapidly expanding market would also speed up the necessary process of regulatory change. New technology that exploits information technology for, e.g. more complex metering such as net metering and automated real time control of domestic energy systems will have to be made available at a commercial scale. This is discussed in Choudhury and Andrews [32]. These technologies are available, but have not been applied on a large scale.

It is also important to note that the literature surveyed above concentrates on the current energy system. Microgrids, however, open up possibilities for dramatic change in the structure of the energy system. Active demand management in response to electricity price signals could not only significantly reduce the peak demands on the network but could also lead to large scale energy savings, introducing a culture favourable to energy efficiency in households.

The present analysis, combining PV and micro-CHP and a very small battery requirement, gives a microgrid that is independent of the national electricity network. This has particular benefits for remote communities. In particular, there would be no further requirement to provide transmission cables. This would remove distribution costs outside the microgrid. It would also have the further benefit in areas of natural beauty of

enabling the removal of unsightly power cables. These factors would increase the social benefit of installing microgrids. This opens up dramatic possibilities. The medium term requirement to replace current generation nuclear and coal fired power stations could be met by this technology. This would require the combination to match the consumer's expectations for supply security with the same low level of interruptions as the grid. There could also be a greatly reduced demand on the transmission and distribution network, which would also lead to large savings in operation and investment in the long run. Microgrids could also be combined with other energy saving measures and appliances, further reducing domestic and office energy demand and GHG emissions. Overall, the conclusion is that microgrids do have real potential to make a major contribution to reducing GHG emissions from buildings, which in the UK are now 50% of final energy demand. This will only happen if there are major changes to the electricity market and regulatory structure.

7. Conclusions

The paper has examined the energy production by small scale generators in close proximity to the energy users, integrated into microgrids. A review of the current status, including an overview of distributed generation has been given, highlighting the views of the electricity and gas regulator (Ofgem) and the electricity industry, and giving a description of relevant regulatory concepts which may evolve into microgrids.

The issues which underpin the concept of microgrid have been examined, including the integral control of the microgrid and the power balance, focusing on the frequency and voltage control as well as the power quality. No less important is the relationship between the microgrid and the local utility, when present, and the control of the interface and of the power flow.

Components of the microgrid have been discussed with emphasis on the generators (fossil fuel generators as well as photovoltaic arrays, fuel cells and inverters), typical domestic load profiles and the importance of diversity, and a discussion of the progress made in resolving the technical and regulatory issues associated with the utility integration issues of small generators.

The quantitative contribution of the paper rests on the analysis of the energy balance in the microgrid. Whilst the power balance is essential for the control of the microgrid, energy storage at the diurnal time scale will be needed to compensate for the mismatch between generation and demand, and to make the most efficient use of the renewable generation and the electricity produced by micro-CHP More fundamentally, an appropriate diversity of generation methods needs to be employed to satisfy the energy demand and permit stand-alone operation, if required, at any time of the year.

Numerical estimates have been made focusing on the microgrid of domestic users powered by small fossil-fuel generators and photovoltaic arrays. A model of the energy consumption in buildings was used to produce typical profiles for space heating, hot water and the electricity consumption. Based on the energy balance between the generation and load, methodology has been developed to determine the optimum combination of the generators and energy storage in the microgrid. To our knowledge, this is the first study

which highlights the importance of energy balance in the design of microgrids. The principal results include the determination of the optimum micro-generation capacity, consisting of 1.37 kWp PV array per household and 45% household ownership of micro-CHP generators. This is the minimum size which can maintain energy balance on a yearly basis if supplemented by energy storage of 2.7 kWh per household. The required micro-CHP ownership might be reduced to some 15% when fuel cells become available as a domestic CHP generator.

The economics of the microgrids has been discussed against the background of the current regulatory and economic framework for distributed generation. The potential future development of microgrids is discussed by means of three scenarios which, in broad terms, describe the likely stages of deployment to their full potential. We find that there is no fundamental technological reason why microgrids cannot contribute an appreciable part of the UK energy demand. Indeed, an estimate of cost indicates that the microgrid considered in this project would supply electricity at a cost comparable with the present unit cost if the current support mechanisms for photovoltaics were maintained.

Although the present paper concentrates on the comparison with current energy system, microgrids open up possibilities for dramatic change in the structure of the energy system. Combining PV and micro-CHP and a very small battery requirement, gives a microgrid that is independent of the national electricity network. In the short term, this has particular benefits for remote communities or areas of natural beauty. More dramatic possibilities open up in the medium to long term. The requirement to replace current generation nuclear and coal fired power stations could be met by this technology, greatly reducing also the demand on the transmission and distribution network. Microgrids provide a direct facility to implement other energy saving measures and appliances, further reducing domestic and office energy demand and GHG emissions.

Overall, the principal conclusion is that microgrids do have real potential to make a major contribution to reducing GHG emissions from buildings. This will only happen if there are major changes to the electricity market and regulatory structure. The policy question is therefore, how to initiate these changes?

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